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# SPACE INTEGRATED CONTROLS EXPERIMENT (SPICE) PROGRAM

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**Final Report**

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**13. ABSTRACT** (*Maximum 200 words*)
The objective of the SPICE program was to demonstrate improvement in precision pointing, tracking, and retargeting by integration of active isolation, active and passive structural control, advanced materials, active optics, and adaptive control. Available funding allowed only the implementation of the active isolation and active structural control. A linear, full-size, and well-characterized precision test-bed was developed to represent a space-based laser beam director structure. Key SPICE subsystem developments included: (1) an optical sensing system to calculate the optical line-of-sight; (2) proof mass actuators of unprecedented stroke and force capability to deliver the control forces to the structure; (3) a finite element model that accurately modeled the 25 flexible structural modes; and (4) a robust hybrid high-authority/low-authority global control system. A series of tests culminated with the attainment of repeatable and robust attenuation of the optical line-of-sight jitter by 77:1 (six independent disturbances) and 128:1 (three independent disturbances) in the band 5 to 500Hz with little spillover into unregulated degrees of freedom. Methods by which system identification and control system design and implementation can be partially automated were investigated in the latter stages of the program.

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# 1.0 INTRODUCTION

This document, the Final Report of the Space Integrated Controls Experiment (SPICE) program (Contract Number F29601-89-C-0015), is an overview of the 73-month (2/23/89 - 3/31/95) program. The documents cited and their bibliographic references contain thorough discussions of the technical issues that are only briefly discussed here.

## 1.1 THE SPICE PROGRAM

The SPICE program was a cost plus award fee task-ordered contract that had as its objective the demonstration of improvement in directed energy weapon precision pointing, tracking, and retargeting by integration of the critical technologies listed in Table 1. Available funding did not permit all of those technologies to be implemented in SPICE. A major advancement in the state of the art in pointing control was achieved in the SPICE Precision Pointing Experiment using active global structural control and the active isolation developed on the Space Active Vibration Isolation (SAVI) program, the predecessor program to SPICE. The final configuration of the precision structure developed in the SPICE program is shown in Figure 1. That structure is a full-size simulator of a space-based laser beam expander. For example, the primary has an average diameter of 5.6m and the tripod legs that support the secondary are ~8m in length. The subsystems that contain the sensors and actuators used in the active control system are themselves extensions of the state of the art and therefore also had to be developed in the SPICE program.

Table 1. Application of critical technologies in SPICE.

| Technology | Application |
|---|---|
| Active isolation | SAVI used both for isolation and disturbance input (Subsection 2.3). |
| Active structural control | An active global control system based on modern control theory demonstrated an unprecedented reduction in LOS jitter caused by input disturbances (Subsection 12.4.6). |
| Passive structural control | Analyses performed and components designed, fabricated, and tested, but technology not implemented on structure (Subsect. 11.4.4) |
| Advanced structural materials | Not used in SPICE. |
| Active optics | Not used in SPICE. |
| Adaptive control | Not used in SPICE. |

## 1.2 SPICE PROGRAM SUBTASK STRUCTURE

The SPICE program was organized into three major task areas: management (01), technical (02), and facilities (03). Each of the task areas was broken down into subtasks. Figure 2 shows

the flow of the program through the various subtasks from requirements development through subsystem development through testing and demonstration of the high authority control (HAC)/low authority control (LAC) global control system.

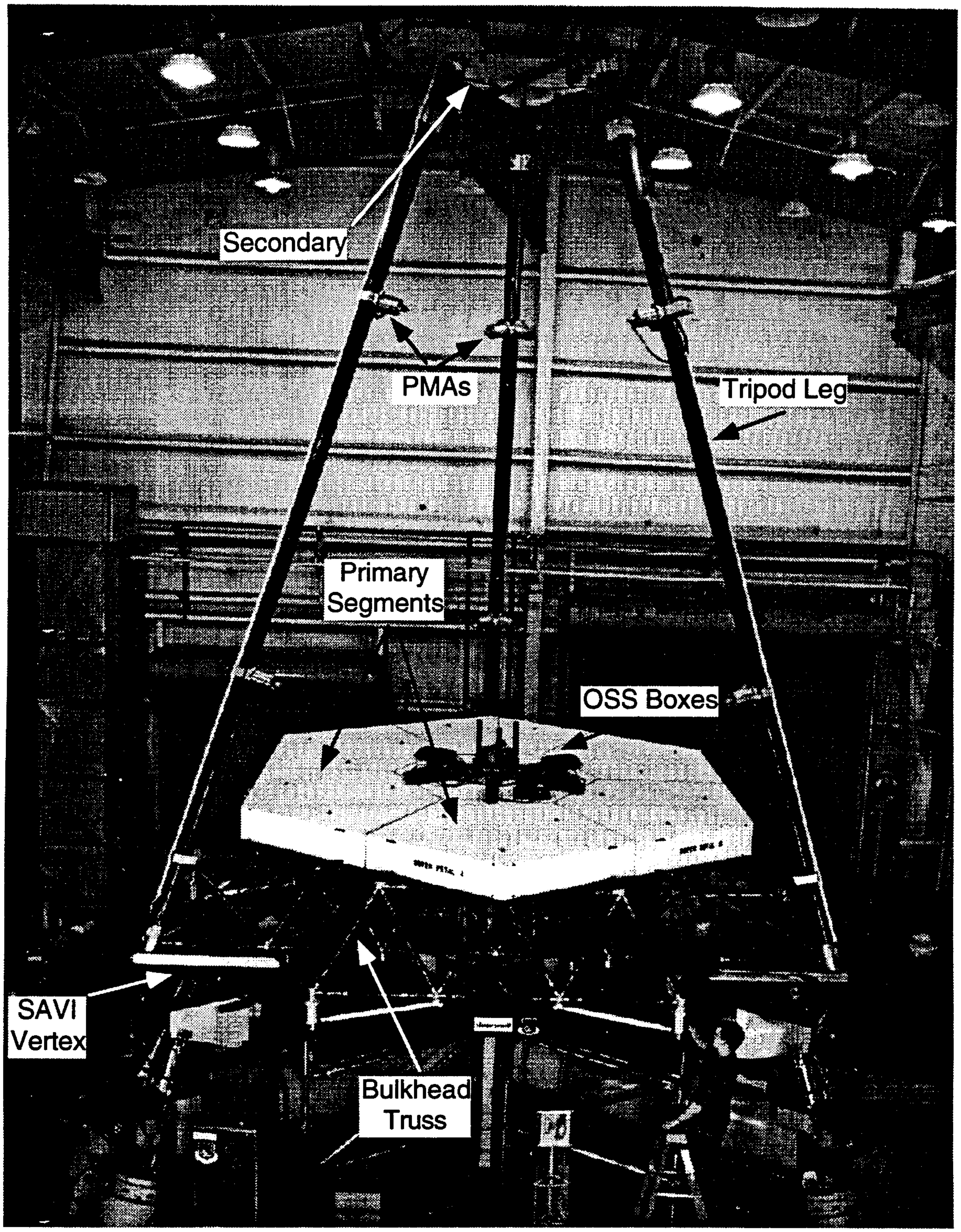


Figure 1. The SPICE structure.

In August, 1993, the HAC/LAC system achieved a 77:1 attenuation of input disturbance effects on the optical line-of-sight (LOS) on a large precision beam expander simulator using 18 proof mass actuators (PMAs) and a suite of nine two-axis optical sensors called the optical sensing system (OSS).

The program overview depicted in Figure 2 is expanded upon in Sections 3 - 18, each of which is a brief description of the approach to--and results of--a SPICE Subtask. The SPICE program also supported other defense programs as indicated at the bottom of Figure 2.

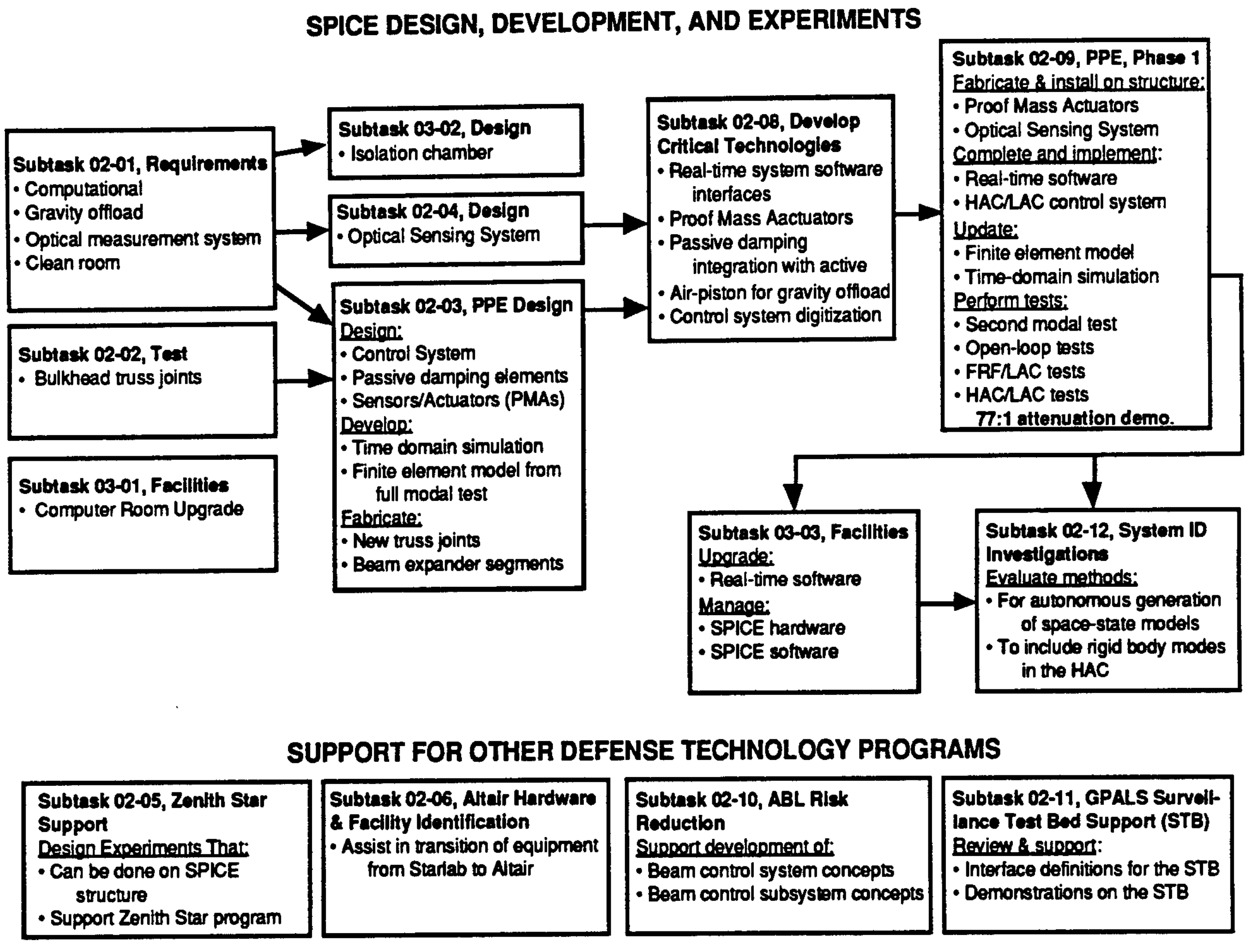


Figure 2. SPICE Technical and Facilities Subtasks.

## 1.3 HIGHLIGHTS OF THE SPICE PROGRAM

The demonstration of active global control on the large SPICE structure was the most visible result of the SPICE program. Attenuation of disturbance-induced LOS jitter by the HAC/LAC control system depended upon efforts in several technology areas which were themselves

outstanding achievements. The following highlights are discussed in this section:

(1) Innovative application of system engineering that enabled this complex program to achieve its goals,

(2) Development, characterization, and finite element modeling of a linear structure that is a full-sized simulator of a space-based laser system,

(3) Design and fabrication of an OSS that met stringent optical measurement sensitivity and dynamic range requirements,

(4) Design, fabrication, and integration into the structure of 18 PMAs that met unprecedented force, stroke, and linearity requirements,

(5) Development of the complex array of software tools required to implement the HAC/LAC system in the real-time computer system and to run it at the required frame and data rates, and

(6) Demonstration of 77:1 root-mean-square (RMS) LOS attenuation by the HAC/LAC system with six independent disturbances and 128:1 with three independent disturbances.

(7) Development and implementation of system identification techniques resulting in test data derived models that were used to demonstrate 97:1 LOS jitter reduction with three independent disturbances.

### 1.3.1 Innovative Application of System Engineering.

The SPICE program was successful primarily because of the consistent application of system engineering principles that were tailored to the program. During preliminary planning for the Precision Pointing Experiment, six rules were established by the chief system engineer that guided the SPICE team through the difficulties that inevitably arise on a complex program that is breaking new ground:

(1) A test series must be planned to support analysis. No data is to be taken that does not have a specific role in this support.

(2) Understanding what occurred in a test is more important than achieving specific results.

(3) Test plans must be detailed because of the interdisciplinary nature of the SPICE team and the SPICE program.

(4) Where feasible, procedures common to several tests are to be documented in detail as modularized procedures.

(5) Data reduction and analysis done in conjunction with a test must be specified in detail to allow rapid turnaround of results.

(6) The Test Director may modify or "red-line" a test plan.

The requirement that the use of data be specified in detail before it was taken was particularly important to the success of the tests. In planning for the open-loop tests it became clear that the extracting and printing of the results of the numerous FRF measurements in a reasonable time, much less evaluating them, was impossible. It was necessary to automate the data review. Data-evaluation tools were therefore developed before the data were taken that allowed essential features to be extracted and to identify problem areas while the tests were still in progress.

The PMA development was especially challenging because of the unprecedented force and stroke requirements. It became clear that the development of a flexure that could meet all of the original PMA specifications would require more resources than were available. The SPICE approach to relaxation of the specifications involved keeping system goals in mind and devising a series of analyses to show which specifications could be relaxed with the least possible impact on those goals. These analyses showed that the system-level objectives could still be met with reductions in the PMA requirements for both flexure linearity and cross-axis stiffness.

### 1.3.2 Development, Characterization, and Modeling of the SPICE Structure

Successful demonstration of the HAC/LAC system depended not only on control system design but also on outstanding structural design, characterization, and modeling. The SPICE structure was painstakingly evaluated and modified over several years to ensure that it would be linear and modelable. For example, all of the end fittings for the links of the bulkhead truss structure were replaced when they were found to exhibit nonlinearity and hysteresis (Ref. 1). The finite element model, which was based upon thorough component-and system-level modal tests, had exceptional fidelity to the structure. It accurately modeled the 25 flexible structural modes covering the entire band of the high authority control system (frequency ≤50 Hz).

### 1.3.3 Design and Fabrication of the OSS

The SPICE program designed, fabricated, and integrated subsystems into a precision structure that simulates a portion of a space-based laser beam control system hierarchy. The pointing system of a real space-based laser would have the task of holding a beam on a distant target, that is, of maintaining the error in the LOS of the optical telescope through which the beam is projected at ≤1μrad RMS. The SPICE program's goal was to perform an affordable demonstration of the pointing technology required of a space-based laser. Mass simulators were designed to be rigid to >100Hz and used in place of the optical elements so that the LOS error

of the SPICE test bed simulated telescope depends, to first order, only on the average tilt of the axis of the primary from the nominal LOS, the tilt of the secondary from the nominal LOS, and the decentration or displacement normal to the LOS of the secondary with respect to the primary. The OSS was successfully designed to measure angles <100nrad and displacements <50μm in a laboratory that had little environmental control.

The high bay of Kirtland Air Force Base Building 765 was the SPICE laboratory. Temperature control in the high bay is unreliable and the retractable door structures on the north and south sides of the laboratory allow some air disturbance into the high bay during windy conditions. OSS probe beams therefore traversed air that was often very turbulent, resulting in noisy measurements of the tilt and decentration of the secondary mirror mass simulator. An isolation chamber was originally planned to surround the SPICE apparatus to control air flow, temperature, and humidity during testing. When resource limitations forced deletion of the chamber, monitoring of motion of the secondary mirror mass simulator had to be done through a 15 m beam path of ambient air. It was necessary that LOS jitter attenuation demonstrations be performed in a range that exceeded the noise level due to air turbulence. Therefore, in tests of the full HAC/LAC controller, the effects of input disturbances on the RMS LOS were attenuated from ~100μrad RMS to ~1μrad RMS per axis. The OSS had to measure <1μrad with good signal-to-noise ratio in closed loop operation and to function at jitter levels 100 times that large with the HAC/LAC control loops open. The former requirement was flowed down to a requirement that total LOS noise due to the OSS be ≤200nrad. As Figure 3 indicates, the OSS met the requirement. Almost all of the OSS measurement noise was due to turbulence in the unshielded air paths of the beams associated with the OSS secondary tilt and translation sensors. The noise contributions by the sensors themselves were negligible.

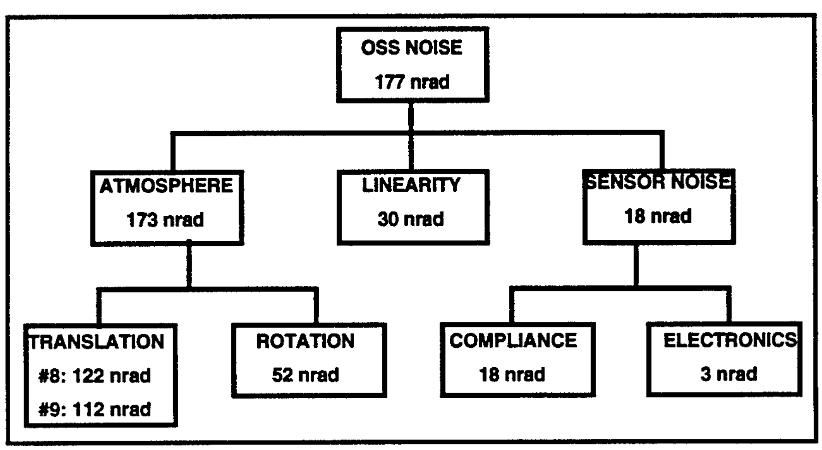


Figure 3. Average OSS noise breakout.

1.3.4 Design, Fabrication, and Integration of PMAs

Eighteen PMAs deliver control forces to the SPICE structure to attenuate the effects of disturbance forces. Four are attached in pairs to each of the tripod legs with the other six distributed around the perimeter of the bulkhead truss. The size of the structure (~3000kg) and the high level of LOS disturbance that had to be attenuated required the SPICE PMAs to be a significant extension of the state of the art in force and stroke capability. A SPICE PMA (Figure 4) is a complex subsystem that includes a housing-mounted accelerometer network that provides the structure rate signals around which the rate-feedback LAC system is closed. Also incorporated into each PMA is a linear variable differential transformer (LVDT), the signals from which are differentiated to provide the velocity of the proof mass relative to its housing at low frequency. At high frequency, the relative rate is calculated by integrating the difference between the housing-mounted accelerometer network signal and that of an accelerometer mounted on the proof mass. The crossover network that combines the two ways of measuring relative rate weighs them equally at 15Hz. A local loop is closed on the relative rate.

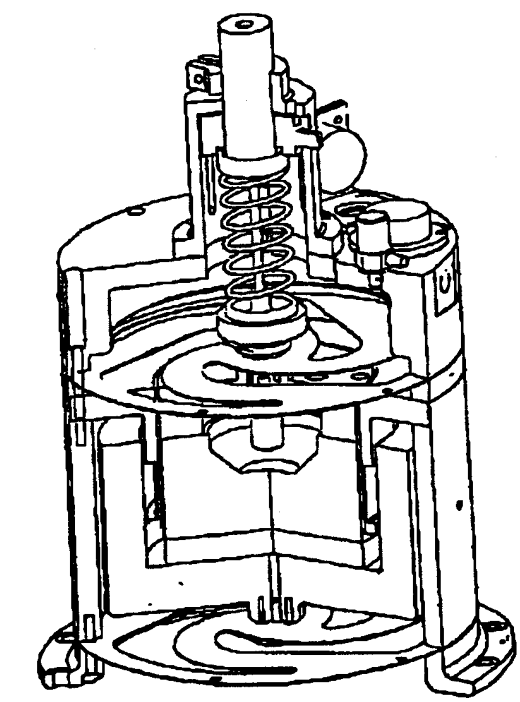

Figure 4. Cutaway view of SPICE PMA.

Besides the unprecedented force and stroke requirements, the final design met stringent specifications on cross-axis modes and force accuracy required for realization of the HAC/LAC system performance goals. Table 2 lists the final top-level PMA requirements. The extensive

effort required to design, fabricate, and integrate these PMAs into the SPICE structure extended over subtasks 02-03, 02-08, and 02-09, the three largest subtasks of the SPICE program. It was brought to a successful conclusion when all control loops were closed and the PMAs performed as modeled to attenuate LOS jitter.

Table 2. Final SPICE PMA specifications.

| | |
|---|---|
| Force | • 40N zero to peak |
| Stroke | • 82kg-mm peak-to-peak stroke-proof mass product |
| Accuracy | • 5% nominal gain, 3% linearity |
| Dynamics | • 1000Hz force response with <60deg. phase loss |
| Mechanical | • In-axis mode frequency = 5Hz ± 20%<br>• All other suspension mode frequencies >90Hz<br>• Housing mode frequencies (between actuator and sensor) >1kHz<br>• No stiction sources |
| Gravity Compensation | • No bias power required in any orientation |
| Integral Sensors | • Proof mass stroke position<br>• Housing acceleration<br>• Proof mass acceleration<br>• Bobbin temperature |

1.3.5 Development of Real-Time Software.

The SPICE apparatus includes a host computer, an array processor, a data bus computer, digital-to-analog converters, analog-to-digital converters, and a high-capacity storage disk, all of which must interact to maintain the high data rates required for the precision pointing experiment. These are collectively known as the real-time system.

Custom interfaces between components had to be devised because standard methods were not compatible with the 1kHz frame rate requirement. Each new experiment placed further demands on the software. For example, in the last series of SPICE tests in Subtask 02-12 (System Identification Investigations), the real-time system, which had been designed to be entered once during a data session, was required to be redesigned to be called repeatedly by the host program. The development of the real-time software to meet every challenge put to it was a *sine qua non* of the SPICE program.

1.3.6 Demonstration of HAC/LAC Attenuation

The Precision Pointing Experiment was the demonstration of attenuation of the effect of input disturbances on RMS LOS error by active structural control. Two of the three elements of the HAC/LAC control system, the local loop and the LAC, are rate-feedback loops that were described in subsection 2.8. Attenuation of RMS LOS error by 8.7:1 was attained through the action of these. The HAC is a global control system that is stabilized by the rate-feedback

loops. The HAC/LAC result of 77:1 attenuation of the effects of input disturbances surpassed the goal of 50:1. The SPICE team had adopted that goal, which exceeds anything previously achieved by a factor of five, before the sensors and actuators were built. This achievement is a validation of global control of a large structure. Figure 5 shows attenuation by LAC and HAC/LAC in a test. Not shown on the figure is the fact that the attenuation in the band of HAC authority (5 - 50Hz) was not achieved at the cost of increased energy in the spillover modes. As part of the system identification study, the SPICE configuration was changed to reflect technology developments in uncooled optics. The three disturbances to the secondary mirror, representing coolant-induced jitter, were removed leaving only the three SAVI isolation leak-through disturbances. Under this configuration, the HAC/LAC control system reduced the LOS by a factor of 128:1.

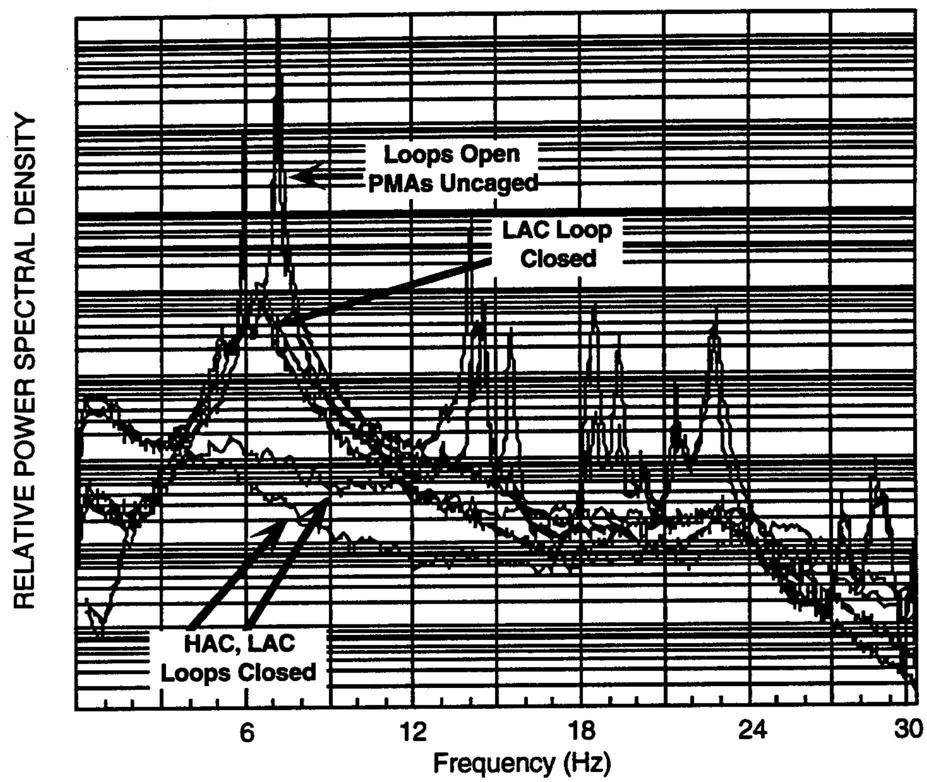


Figure 5. Decrease in LOS x- and y-PSDs as LAC and HAC loops are activated.

### 1.3.7 System ID Demonstration

The system identification (ID) study advanced the state-of-the-art in autonomous system identification by developing and implementing a novel system identification method called Principal Gain Tracking (PGT). The study also successfully applied modal test methods and

Government owned Leuven Measurement Systems (LMS) software to the system identification process.

Both the PGT and LMS methods resulted in state space models that were then used to design HAC/LAC global structural control systems. The PGT system reduced the SPICE telescope LOS jitter by a factor of 97:1, and the LMS method reduced LOS jitter by a factor of 50:1, both in the 5 to 128Hz frequency band. Performance of both of these systems is somewhat worse than the finite element model developed controller that reduced LOS jitter by a factor of 128:1 for the same hardware configuration. With a minimal improvement and refinement effort, we believe the system identification method will equal the finite element method.

## 2.0 SPICE SYSTEM TECHNOLOGY

Figure 6 depicts the SPICE program integration of technologies critical to precision pointing and tracking on a full-scale representative space-based laser structure. The arrows connecting "FINITE ELEMENT MODELS" and "HAC/LAC CONTROL SYSTEM" to the real-time system at the left of the figure are intended to convey their relationship in a pictorial manner. The finite element models of the SPICE structure were an essential ingredient in the development of the control system which was implemented as a single matrix multiply in the array processor of the real-time computer system. The OSS is represented by four of its nine sensor boxes. The "REAL-TIME COMPUTER SYSTEM" box represents not only computers but also the interface electronics and the software that enables the complex system to function at 1kHz. The following subsections provide more detail on each of the technology areas shown in Figure 6.

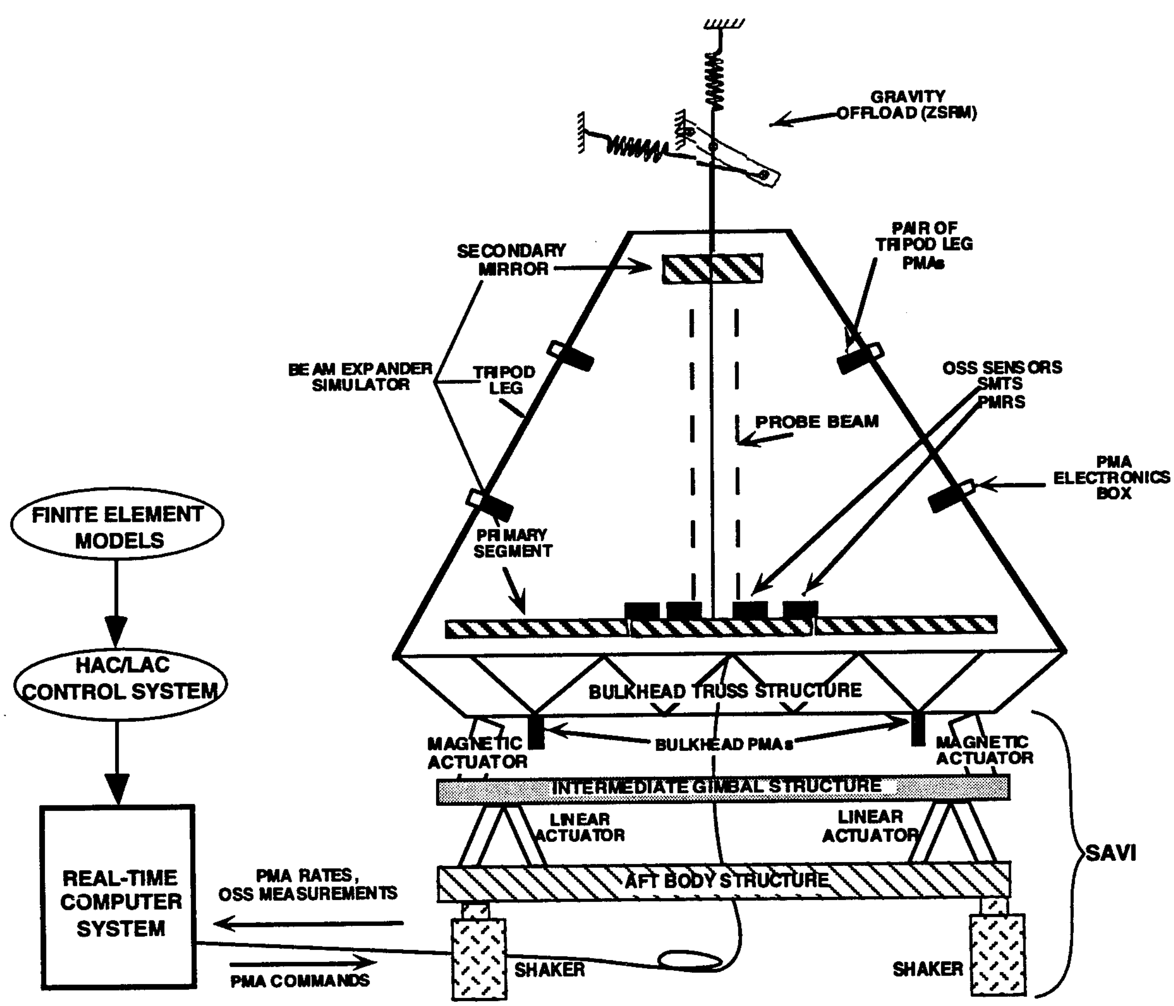


Figure 6. SPICE Technologies.

## 2.1 STRUCTURAL TEST ARTICLE

The SPICE structural test article is a dynamically scaled representation of a space-based laser beam expander. The test article consists of a two-level bulkhead truss which supports a seven segment primary mirror mass simulator and three tripod legs which support a secondary mirror mass simulator at the apex. The dimensions of the test article are: 8.1m in height, 6.2m in diameter, with a 5.6m diameter primary mirror mass simulator. The fully loaded final configuration of the test article weighed ~2,930kg (6,450lbs). The entire test article is suspended from a zero spring rate mechanism (ZSRM) gravity offload device (described in subsection 2.4) to simulate the "free-free" boundary conditions of space. This test article was originally developed for the Space Active Vibration Isolation (SAVI) program. It was substantially modified on the SPICE program to make it a linear, modelable structure on which a high authority control system could be designed and implemented.

The bulkhead truss consists of 234 graphite epoxy struts with steel end fittings, 1.0m in length and 5cm in diameter, connected to 64 aluminum node balls forming a polyhedral truss with hexagonal upper and lower decks. The truss circumscribes a circle 6.2m in diameter and is 0.765m thick. The original bulkhead design contained "one-handed" quick connect joints to show traceability to manned construction in space. Unfortunately, these joints behaved poorly due to tolerance stack-up problems which resulted in non-linear, hysteric performance (Ref. 1). A decision was made to replace these joints with the current steel end fittings to get more linear performance out of the system. The struts with the new end fittings showed <10% variation in stiffness when the lot was tested (Ref. 2, 3).

In addition to the 234 one meter struts, 27 specialized struts are used to form connections to the three tripod legs. At the interface between the bulkhead and each tripod leg, there are three pairs of custom struts forming the interface for a total of 18 struts. The other nine are located at the top of the test article and are used to separate the tops of the tripod legs at a prescribed distance necessary to allow the SAVI device to retarget the test article ±2 degrees in the presence of the ZSRM support cable. Between the top of each pair of tripod legs, there are three struts which form a Z-shaped pattern.

The top level of the bulkhead truss forms the mounting plane for the segmented primary mirror mass simulator. The six outer pentagonal petals are connected to the bulkhead at three node ball locations. The central hexagonal shaped petal is connected to the bulkhead by three specially

heat tempered node balls of higher strength. These are powder-coated red to set them apart from the other node balls. These node balls have to be of higher strength because they form the primary load path between the bulkhead and the ZSRM. The ZSRM double pivoted gimbal is attached directly to the central petal. The segments were all designed to have a fundamental frequency >100Hz (Ref. 4) The outer segments on average weigh 170.5kg while the central segment weighs 190kg.

The tripod legs are 17.8cm outer diameter, 0.36cm thick graphite epoxy tubes 8.3m in overall length. The graphite epoxy tubes have 14 layers of 0.25mm graphite windings. The ends of the tubes contain solid aluminum plugs which have tapped hole patterns for attachment to the SAVI device interface plates.

The secondary mirror mass simulator is a triangular shape with locking clamps at the vertices to connect to the tripod legs. The center of the mass simulator contains an 18in. diameter hole to accommodate the ZSRM support cable. This 135kg simulator also meets the requirement that its fundamental frequency be >100Hz.

2.2 OSS

The OSS, as discussed in subsection 1.3.3, is the optical measurement subsystem of the SPICE apparatus. It was designed in Subtask 02-04 to determine the LOS of the beam expander simulator. The RMS LOS error of the beam expander simulator is the cost function minimized by the HAC/LAC control system.

The OSS sensors measure the quantities needed to calculate the LOS under the assumption that all segments are rigid within the frequency band of interest. To first order, the LOS of the beam expander simulator is given by:

$$\varepsilon = \frac{2}{7}\sum_{j=1}^{6}\Theta_j - \frac{2}{M}\Theta_S + \frac{1}{f_p}\left\{\frac{T_1+T_2}{2}\right\} \tag{1}$$

in which the two-vectors in the equation are defined as:

$\varepsilon$ = Tilt from nominal of the LOS,
$\Theta_j$ = Angular tilt from nominal of primary mirror segment j,
$\Theta_S$ = Angular tilt from nominal of the secondary mirror,
$T_i$ = Translation of tracked point i on the secondary.

and the scalar quantities are given by:

$M$ = Telescope magnification,

$f_p$ = Primary mirror focal length.

The OSS is a suite of custom sensors composed of:

- Six two-axis primary mirror rotation sensors (PMRSs) that measure the six $\Theta_j$,
- One two-axis secondary mirror rotation sensors (SMRS) that measures $\Theta_S$, and
- Two two-axis secondary mirror translation sensors (SMTSs) that measure the $T_i$.

All OSS measurements are relative to the primary center segment. The tilt of an outer segment is measured by using a diode laser beam that originates in a PMRS box on the center segment and is reflected from a flat mirror attached to the outer segment and thence back to a position-sensitive detector in the same box. Secondary tilt is measured using a collimated beam that reflects from a flat on the secondary back to the SMRS. Measurement of lateral displacement or decentration of the secondary requires tracking of two points on it to allow determination of displacement of its geometric center in the presence of rotation about the optic axis. Two slightly focused beams that are retroreflected from corner cubes on the secondary to a focus ~10in. above their respective SMTS entrance apertures enable these measurements top be made. The locations of the sensor boxes on the primary center segment are shown in Figure 7. Figure 8 shows the secondary and the locations of the reflector elements mentioned in the preceding paragraph. The design and performance of the OSS are discussed in References 5 and 6.

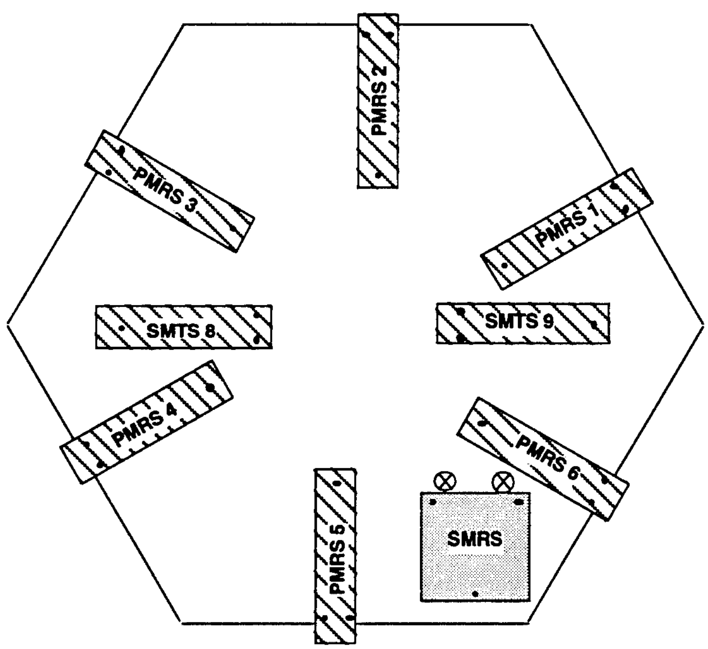


Figure 7. SPICE primary center segment with OSS Sensors.

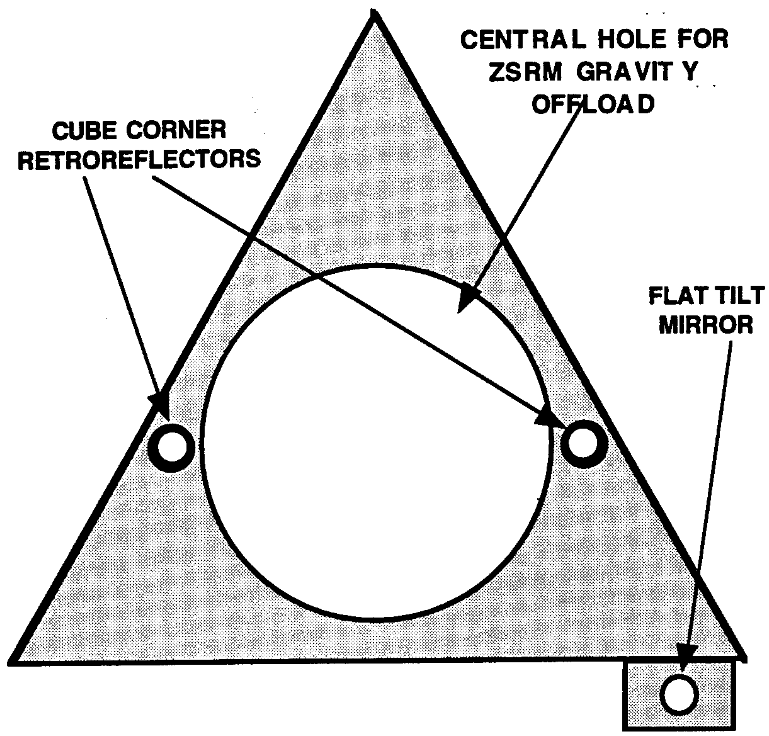


Figure 8. SPICE secondary mirror mass simulator.

Table 3 shows the final set of OSS requirements determined in Subtask 02-04. The noise requirements were challenging because a planned isolation chamber for the experiments was deleted due to funding limitations.

Table 3. OSS final requirements

| | Requirement | Description |
|---|---|---|
| Measurements | 16 | Secondary rotation (2) & translation (2), tilt of six primary segments (12) |
| Sample rate | 1000/s | After analog-to-digital conversion |
| LOS range | ±300 μrad | In output space |
| LOS precision | 200 nrad | RMS in output space |
| Ambient disturbance | 0.1g | RMS broadband |
| Ambient temperature | 60 - 80 deg F | |
| Experiment duration | 15 min | Maximum |
| Output signal range | ±10 V | Analog output |
| OSS structural modes | >100 Hz | First bending mode |

The sensors monitoring degrees of freedom of the secondary depend upon beams that pass through ~15m of unshielded ambient air. Noise due to air turbulence is appreciable but, in spite of that, these sensors have met all requirements.

## 2.3 SPACE ACTIVE VIBRATION ISOLATION (SAVI).

The SAVI subsystem controls the six rigid body degrees of freedom of the SPICE structure. It was developed in the SAVI program, the predecessor to the SPICE program. The SAVI system was designed to isolate the beam expander from disturbances originating in other parts of the space vehicle and to provide limited pointing. Reference 7 is a comprehensive discussion of the design and development of that subsystem.

In a space-based laser system, the high energy laser device would be located in the aft body (lower part of Figures 1 and 6) and it (and any other on-board sources of vibration) would cause beam expander LOS error. The SAVI uses magnetic actuators (Fig. 9) to isolate the fore body from aft-body disturbances. These actuators are also used with magnetic gap sensors in closed-loop control of the six rigid body degrees of freedom of the SPICE beam expander simulator. A modification was made during the SPICE program to enable these same actuators to be used to impart band-limited random and sine wave disturbances into the structure. The SAVI system also includes large-stroke linear actuators that, together with the magnetic actuators, allow ±2deg retargeting of the beam expander. The linear actuators were not used in SPICE.

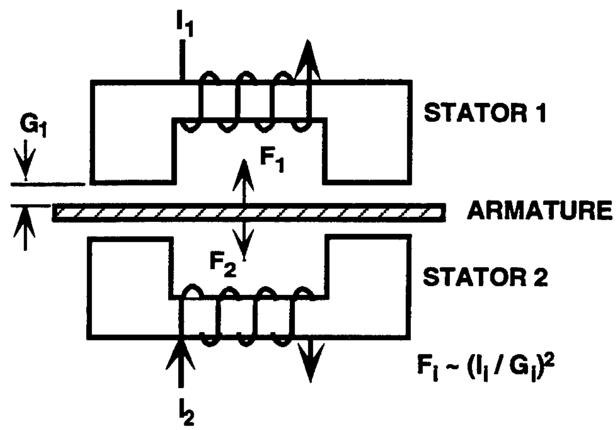


Figure 9. SAVI magnetic actuator principle.

## 2.4 GRAVITY OFFLOAD

An orbiting device is weightless. To maintain traceability to a space-based system, the weight of a ground-based test bed system must be offloaded, i.e., the system must not support its own weight. The nearly 3000kg SPICE structure is attached via a rod to a ZSRM that is housed in a shelter or cupola atop the roof of the test cell. The ZSRM is composed of two springs that are in balance over the operating range. As the suspended mass is displaced, one of them exerts a restoring force but the other exerts an equal and opposite force (Fig. 10). This in principle eliminates restoring force and unwanted longitudinal vibrational modes. The ZSRM was inherited from the SAVI program and the final report of that program contains a detailed description of it (Ref. 6).

The ZSRM performed satisfactorily in SPICE, as would be expected for a well-proven technology that has been used since the 1960s to simulate the weightlessness of space. A pneumatic floor-standing device, a more recently developed gravity offload technology, was also investigated in SPICE (Ref. 8). Three floor-mounted devices would support the SPICE structure around its periphery. Obvious advantages of such a system over a ZSRM include improved traceability to a space-based system through elimination of pendulum modes and removal of interference with the optical axis of the beam expander structure. Reference 8 describes the pneumatic suspension system and presents its advantages and disadvantages vis-a-vis the considerably more mature ZSRM technology.

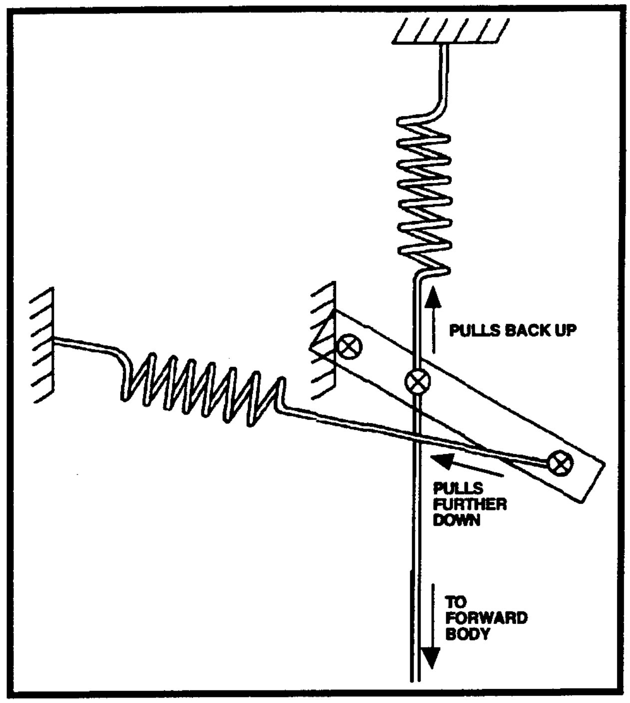

Figure 10. Principle of ZSRM.

2.5 PMAs

The function of the PMAs was introduced in subsection 1.3.4. The design (Subtask 02-03), development (Subtask 02-08), and fabrication and integration into the SPICE precision structure (Subtask 02-09) were presented there as a highlight of the SPICE program. Development of the SPICE PMA was a significant technology effort, not simply a procurement. The specifications for force and stroke (Table 2) represented extensions beyond the state of the art for such a device. Moreover, cross-axis and parasitic performance parameters, which are often left uncontrolled, were recognized as crucial to the success of the Precision Pointing Experiment and were therefore specified precisely as well. The PMA development effort is discussed extensively in the PMA Final Report (Ref. 9).

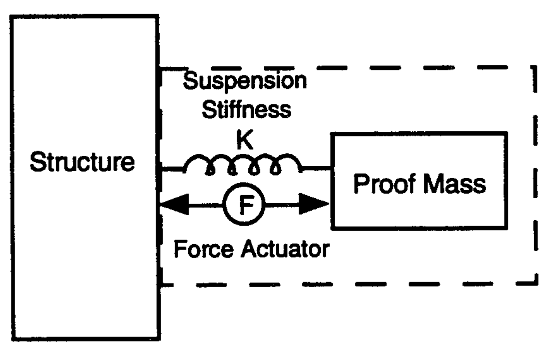

Figure 11. PMA exerts inertial force

The PMA is capable of applying an inertial force to a body (Fig. 11) which is particularly useful for the active control of flexible structures. Inside the device, a heavy mass called the proof mass is weakly suspended from the housing in one degree of freedom. A voice coil force actuator pushes on the proof mass when electric current is applied to its coil. While pushing on the proof mass, the voice coil also reacts against the housing and thus anything to which the housing is attached, i.e., the SPICE beam expander structure. Figure 4 is a cutaway view of the SPICE PMA subsystem.

## 2.6 STRUCTURAL MODELS

The SPICE program emphasized careful characterization of the structure. Finite element modeling using NASTRAN was begun early in the program and, as subsystems such as the PMAs and the OSS were added to the structure, mass models were added to it to maintain its currency. Full modal tests were performed in Subtask 02-03 and in Subtask 02-09 to allow validation and tuning of the finite element model. A PATRAN-based model developed by government personnel provided a cross-check for the model used in the control system design.

SPICE finite element modeling began with modification of SAVI1, a model inherited from the SAVI program. Successive upgrades resulted in models of increasing fidelity to the final Precision Pointing Experiment structure until, at SPICE4, a finite element model was developed that was reconciled with the full modal test performed during Subtask 02-03. Table 4 summarizes SPICE finite element modeling. Discussions of the SPICE2 and SPICE3 structural models may be found in References 10 and 11. The reconciliation of the SPICE4 models with the modal test is discussed in Reference 12.

The last of the SPICE finite element models, the SPICE5 models, was reconciled to a full modal test of the structure in its final Precision Pointing Experiment, Phase 1 configuration. The SPICE5 models had excellent fidelity to the modal test for modal frequency ≤50Hz which turned out to be ample for design of the successful HAC. Reference 13 includes the model/structure mode correlation.

Table 4. Evolution of SPICE Finite Element Models

| Finite Element Model | Description |
|---|---|
| SAVI1 | Model of forebody of SAVI apparatus |
| SPICE1 | SAVI1 with first models of segmented primary |
| SPICE2 | • Measured node ball and strut masses<br>• Tripod leg models<br>• Circular Primary center segment model with 1st mode @ 100Hz<br>• Primary outer segment model with 1st mode @ 100Hz<br>• Flat triangular secondary model with 1st mode @ 100Hz<br>• SAVI/SPICE interface plate |
| SPICE3 | • Detailed finite element model of secondary design<br>• Detailed finite element model of primary center segment design<br>• Detailed finite element model of primary outer segment design<br>• Measured axial stiffnesses of truss links used<br>• Tripod leg component modal test results incorporated into leg finite element model<br>• Increased detail of SAVI magnetic actuator interface<br>• Mass models of OSS |
| SPICE4A<br>SPICE4C | • Refined models of bulkhead truss links<br>• Connections between model components include appropriate flexibility<br>• PMA models updated to latest design data<br>• System finite element model correlated to results of first modal test<br>• Mass/spring simulators of PMAs added (SPICE4A only) |
| SPICE5 | • Model of Final PMA<br>• Some structural and mass property updates<br>• Correlated (i.e., tuned) to final Precision Pointing Experiment modal test |

## 2.7 CONTROL SYSTEM

The HAC/LAC control system that was successfully used in the Precision Pointing Experiment is three-tiered. A local loop and a LAC loop are collocated with the PMA. The former (Fig.12)

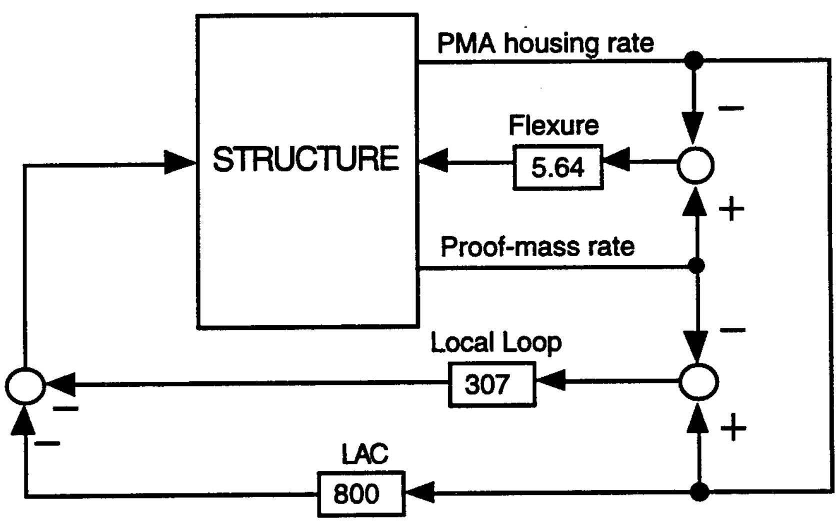


Figure 12. Model of local and LAC loops (rate gains in N-s/m).

is closed on the relative rate between the proof mass and the housing. The PMA housing is rigidly attached to the structure so the housing rate equals the structure rate at the PMA. The PMA imparts a relative force between proof mass and housing (see Fig. 11) so the local loops are inherently stable. The LAC loops have higher gain and, because they use only the housing rate as the error signal, they are not inherently stable. However, with the gains chosen, the LAC plus local loop combination is stable.

The HAC is a global controller that was implemented in the Star array processor as a single matrix multiply (Ref. 14, 15). (Figure 13 summarizes the entire closed-loop system model.) A standard linear quadratic Gaussian regulator was used to minimized. However it was found to be necessary to include torsion of the secondary mirror about the optical axis in the cost function. The first flexible mode of the structure (other than PMA proof mass modes) is mainly torsion about the optical axis which results in very little LOS disturbance yet is very easy to excite with PMA forces. Significant spillover into the torsion mode due to small model errors could be eliminated only by including torsion in the cost function. A perfect structural model would have eliminated this necessity but the essence of HAC design philosophy is that it be

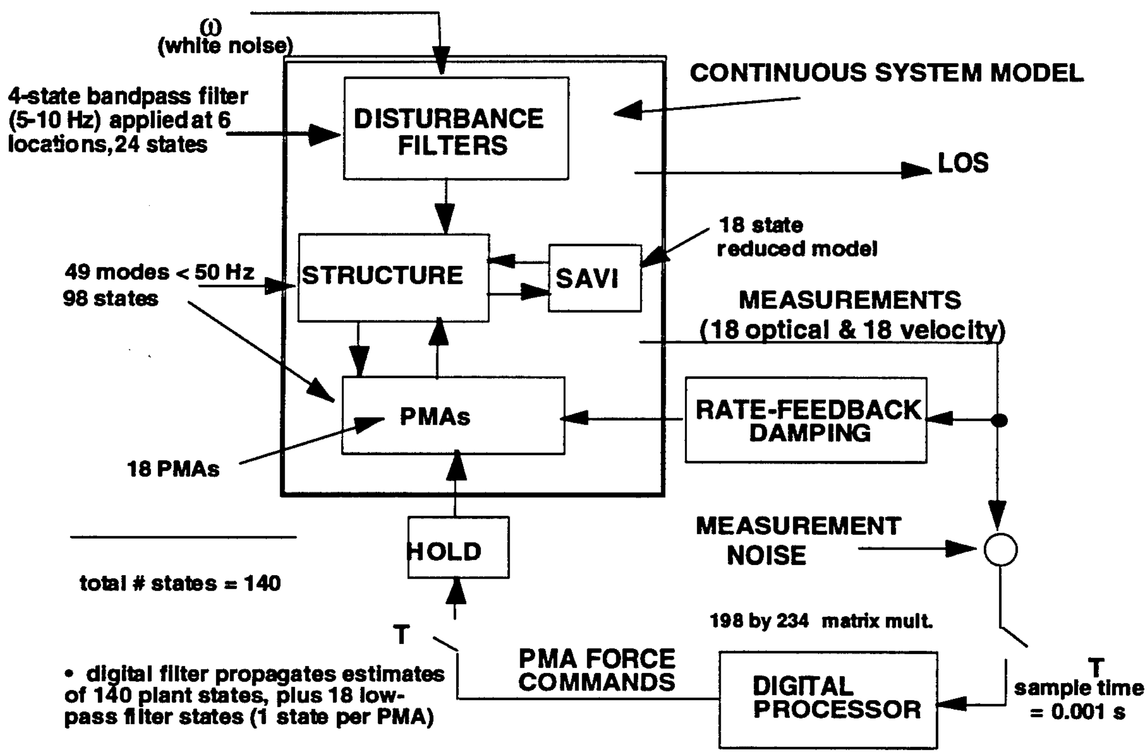


Figure 13. The HAC closed-loop system model.

robust to small model errors. An extended discussion of the design and implementation of the HAC is contained in Reference 15.

## 2.8 SPICE REAL-TIME SYSTEM

The heart of the Precision Pointing Experiment is the real-time system consisting of computer hardware and associated critical components:

- VAX 11/780
- Star VP-3 Array Processor
- Aptec IOC-24 Input/Output Computer (6 Input/Output Processors)
- Tustin System 2100 Digital-to-Analog Converter
- Tustin System 2100 Analog-to-Digital Converter
- Concepts C-51 High Speed Disk Drive (2.5Gbyte)

These are configured as shown in Figure 14. Two Aptec Input/Output Processors are connected to the Star array processor to support the large data rate requirements and the Input/Output overhead penalty associated with the Star.

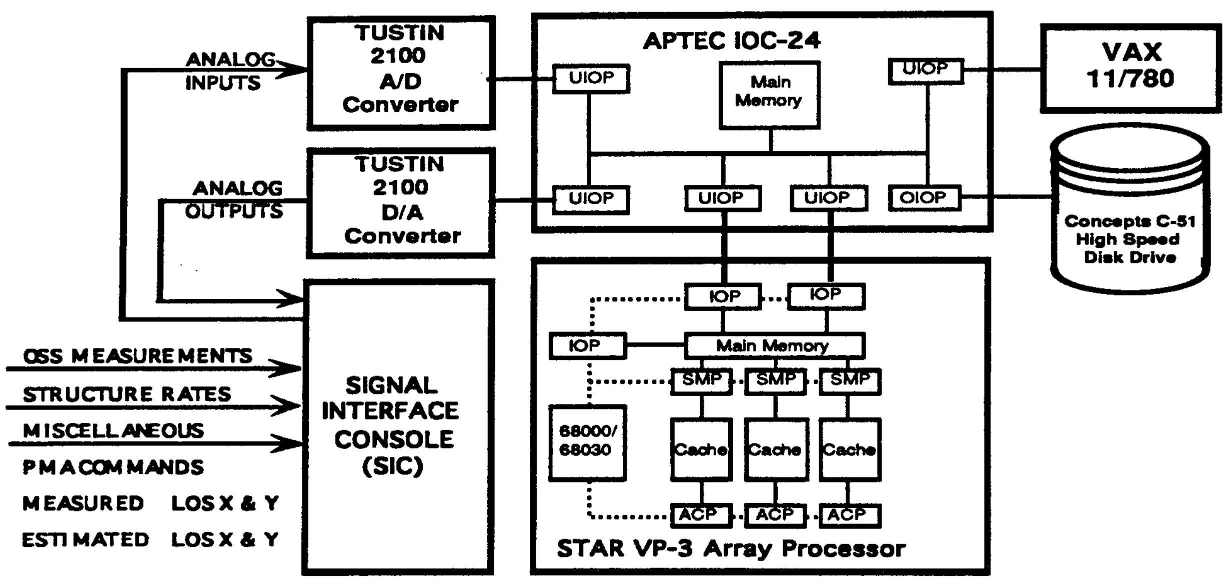


Figure 14. The SPICE digital control system hardware.

The development of the SPICE real-time system software is discussed in subsection 1.3.5 as a highlight of the program. For a description of the software itself, see Reference 16.

## 2.9 PASSIVE DAMPING

In active structural control, attenuation of disturbance effects is achieved through forces that are calculated and delivered to the structure through actuators, that is, attenuation is achieved by active elements. Passive damping refers to the attenuation of structural motion by elements attached to it that, by design, cause the structure to be dissipative in certain frequency ranges. An example of this is a viscoelastic layer applied to the outer layer of a structural member that dissipates energy when the member is bent.

The final HAC/LAC system (with three independent disturbances) achieved 128:1 attenuation of the effect of input disturbance forces in the band 5 - 500Hz by active control alone. To effect greater attenuation, it will be necessary to increase HAC gains which will increase the possibility of instability due to pumping of spillover modes, i.e., modes not included in the HAC. Preliminary analysis indicates that 2% damping of 12 modes will amply stabilize the control system, allowing 200:1 attenuation of line-of-sight. The approach planned for Phase 2 of the Precision Pointing Experiment was to increase HAC gains and to passively damp prominent spillover modes by the incorporation of damping struts into the SPICE bulkhead structure in combination with constrained layer treatments on the tripod legs and, in some concepts, tuned mass dampers. Two strut designs were investigated analytically and through prototype component testing in the laboratory. One of these, the V-strut, was based upon viscoelastic damping, the other, the D-strut, on viscous damping. Both were found to be potentially suitable with the former nearly meeting all requirements without having been optimized. A three-parameter model was used to model a typical damped strut. This provided a simple representation of the strut stiffness and damping characteristics and allowed sizing of the strut parameters to match the stiffness, damping, and frequency characteristics to match the system-level damping requirements. Constrained layer design was modeled using finite element and modal strain energy methods. Development was halted early in Subtask 02/09 due to resource limitations. Reference 16 is a thorough discussion of the development of passive structural damping technology in the SPICE program.

## 2.10 INTERFACE ELECTRONICS

The design, fabrication, integration, and testing of cabling and electronics to interconnect, power, and control the various parts of the system involved >2mi of cable, almost 10,000 electronic parts, hundreds of connectors, and more than 100 pages of drawings. The handling of control, telemetry, and fault monitoring functions required a dedicated computer interfaced to 20 other distributed microprocessors and various analog multiplexers, and the development of

appropriate software. The development of the SPICE electronics is documented in the SPICE Electronics Report (Ref. 18) and its bibliographic references.

The goal of the SPICE Precision Pointing Experiment was to demonstrate significant reductions in measured analog signals from the system sensors using a control system with a bandwidth near 60Hz. It was therefore of paramount importance to have noise-free transfer of analog signals throughout the system and to avoid data contamination by 60Hz electric line signals. In the SPICE system:

- Every command/telemetry signal was transmitted using balanced differential line drivers and receivers with three-conductor "twin-ax" cables, and
- No 60Hz power was distributed anywhere on the structure; a direct current (DC) power bus drove local DC-to-DC converters for electronics supplies where needed.

Extremely clean analog signals throughout the system resulted from these efforts. Electronic noise was ~1 to 2mv RMS, and no 60Hz spikes were observed on measured power spectral densities (PSDs) in any of the system-level tests.

# 3.0 SPICE SUBTASK 01-01 - PROGRAM MANAGEMENT AND ADMINISTRATION

## 3.1 SUBTASK OBJECTIVES

The objectives of this subtask were to provide effective and efficient management and administration for all SPICE subtasks and to provide temporary office space for Contractor personnel.

## 3.2 PERIOD OF PERFORMANCE

Subtask 01-01 was active from 30 May 1989 through 31 March 1995.

## 3.3 SUBTASK APPROACH

The subtask was divided into eight technical tasks:

(1) Program management,
(2) Subtask proposal preparation,
(3) Cost and schedule status reporting,
(4) Site management and administration,
(5) System safety,
(6) Computer code management,
(7) Provision of temporary office space, and
(8) Final report.

## 3.4 SUBTASK RESULTS AND DISCUSSION.

The tasks contained in this subtask are necessary for the performance of a medium-sized engineering program. Accurate planning enabled SPICE to perform technical tasks on schedule, within budget, and without interruption of effort. All contract data required list items and other documents were delivered on schedule. A formal facility safety plan was prepared that included emergency procedures, safety checklists, and personnel safety orientation procedures (Ref. 19).

# 4.0 SPICE SUBTASK 02-01 - SYSTEMS REQUIREMENTS STUDY

## 4.1 SUBTASK OBJECTIVES

The objective of this subtask was to develop, through analyses, the requirements for the computers, gravity offload system, optical measurements system, and isolation chamber to be used to perform integrated acquisition, tracking, pointing, and fire control experiments.

## 4.2 PERIOD OF PERFORMANCE

Subtask 02-01 was active from 2 May 1989 through 5 October 1989.

## 4.3 SUBTASK APPROACH

The subtask was divided into four tasks corresponding to the four areas in which requirements were to be determined, namely, computers, gravity offload, optical measurements, and isolation chamber.

### 4.3.1 Approach to Computer Requirements.

A survey of available documentation from related programs such as Joint Optics Structures Experiment (JOSE), Integrated Acquisition Tracking and Controls Simulation (IATACS), and SAVI was performed. The information derived therefrom was instrumental in the determination of controller processing requirements which were, in turn, flowed down to specific computer hardware requirements.

### 4.3.2 Approach to Gravity Offload Requirements.

A study of the ambient environment of the SPICE laboratory established the parameters to be used in a tradeoff study of the pre-existing single point ZSRM suspension from above and a three-point suspension from below.

### 4.3.3 Approach to Optical Measurements System Requirements.

A preliminary point design of the OSS sensor suite was performed to study in simulation the effects of parameter variations. The information gained from the simulation work and other analyses as well as a review of applicable literature led to the definition of an initial set of requirements for the optical sensors.

4.3.4 Approach to Isolation Chamber Requirements.

A survey was performed of the clean room requirements of related experiments such as Large Optics Demonstration Experiment (LODE), SAVI, and IATACS. The results of the survey together with the available environmental data for the SPICE laboratory and analytical results concerning environment requirements for the OSS generated the inputs to building modification plans.

## 4.4 SUBTASK RESULTS AND DISCUSSION.

(1) Computer requirements for active structural control were derived assuming implementation of the controller as a 100 by 132 matrix at 2000 Hz frame rate. The 100-vector output consists of 80 states and 20 commands. The 132-vector input consists of the 100 elements of the previous output vector augmented by 32 measurements. The requirements were flowed down to recommended hardware components - such as the Star VP-3 array processor and the Aptec IO-24 data bus - that were subsequently acquired and used in the SPICE real-time system.

(2) The gravity offload system trade studies concluded that the ZSRM was a cost-effective offload system for SPICE because it was already in hand, having been used in the SAVI program, and because it met most of the requirements identified. A more advanced device such as the pneumatic floor-standing system discussed in subsection 2.4 could be an improvement in that it would not interfere with the beam expander LOS.

(3) The OSS requirements developed in this effort included: (1)-precision of $<300$nrad and field of view of $\pm 200\mu$rad for a jitter sensor, and (2)-$\pm 100\mu$m precision and $\pm 100\mu$rad field of view for the secondary translation sensor.

(4) A set of isolation chamber environment requirements for the SPICE system was developed including filtration, air conditioning, heat disposal, and vapor barriers.

All four areas of this seminal requirements study are discussed fully in Reference 20.

# 5.0 SPICE SUBTASK 02-02 - TESTING OF TRUSS JOINTS

## 5.1 SUBTASK OBJECTIVE

This subtask's objective was to determine whether or not the bulkhead truss links that were inherited from the SAVI program had the linearity, repeatability and uniformity required in a precision structure.

## 5.2 PERIOD OF PERFORMANCE

Subtask 02-02 was active from 14 August 1989 through 30 March 1990.

## 5.3 SUBTASK APPROACH.

Links were removed from the truss and subjected to tests based upon the principle of direct complex stiffness measurements. The testing was performed by CSA Engineering at their San Jose, California facility.

## 5.4 SUBTASK RESULTS AND DISCUSSION.

The innovative SAVI quick-connect truss links were originally designed to be tightened by hand. In fact, it proved necessary to use torque wrenches to assemble the SAVI truss structure but the procedure was simple and these were still referred to as quick-connect links. All nine of the links tested showed unacceptable levels of hysteresis, nonlinearity, and variation in stiffness from link to link when attached by standard means to the test equipment. Four of the links proved unacceptable even when tightened with custom tools and procedures developed during testing. It was also noted that the links showed some deterioration from the application of the torque required to tighten them sufficiently for them to behave linearly. The requirement to replace the joints on the bulkhead truss links was established on this subtask. Reference 1 discusses the test methodology and presents the results and conclusions of the link tests.

# 6.0 SPICE SUBTASK 02-03 - PRECISION POINTING EXPERIMENT DESIGN

## 6.1 SUBTASK OBJECTIVE

The objective of this subtask was to design a precision pointing experiment to be implemented on the SPICE structure.

## 6.2 PERIOD OF PERFORMANCE

Subtask 02-03 was active from 4 January 1990 through 24 March 1992.

## 6.3 SUBTASK APPROACH.

The Precision Pointing Experiment Design subtask was second in scope and resources only to Subtask 02-09, the subtask in which the Precision Pointing Experiment was completed. Nine technical task areas were identified and pursued in parallel to Preliminary Design Review (PDR) level:

(1) Performance of modal tests on the structure,
(2) Correlation of the finite element structural model with the modal test results,
(3) Design of a precision pointing control system,
(4) Development of a time and frequency domain simulation of the Precision Pointing Experiment,
(5) Operation and maintenance of Integrated Structural Modeling,
(6) Design of passive damping elements,
(7) Selection of final designs and sources for sensors and actuators,
(8) Analysis, design, fabrication, and testing of new truss joints, and
(9) Design and fabrication of beam expander segments.

## 6.4 SUBTASK RESULTS AND DISCUSSION.

The PDR proceedings (Ref. 21) presents the results of tasks 3, 4, and 6-9. Tasks 1 and 2 were extended for approximately one year after the PDR. Task 5 was discontinued early in the subtask.

### 6.4.1 Modal Test

Modal tests were performed on the tripod legs, the bulkhead subassembly, and the primary and secondary mirror mass simulators of the SPICE structure. The results of these tests served as input to the finite element modeling effort. The structure was then assembled and a full modal

test was performed. The SMRS and a single PMRS were installed, as were mass simulators of the other PMRSs and the SMTSs. Two shakers, one attached to the top of tripod leg 1 with its axis horizontal and the other attached to the bulkhead with its axis vertical, imparted burst random excitation to the structure. Response degrees of freedom numbered 487 including the four optical measurements. The government-owned modal system, composed of a DIFA/Scadas front end and an HP9000/370 running the Leuven Measurement System software, was used for data acquisition and subsequent curve-fitting of the modes. Thirty flexible modes were identified. Reference 7 discusses the component tests and Reference 22 reports on the system modal test.

### 6.4.2 Finite Element Modeling

In the SAVI program, the beam expander structure was designed to provide a test of SAVI's isolating capability. The SPICE structural models had started with the SAVI structural model and been successively updated as the structure evolved from SAVI special test equipment into the SPICE precision structure. Discussions of these earlier models may be found in References 10 and 11. In Subtask 02-03, two finite element models were developed. One, called SPICE4C, was intended to be a model of the structure as tested in the modal tests discussed in subsection 6.4.1. It achieved excellent correlation with the modal test in the 30 flexible modes from 8 - 75Hz. In the other model, SPICE4A, masses and springs were added to the model of the structure to simulate the PMAs which were not yet available. This was done to gain insight into the mode changes to be expected when the PMAs were installed. The reconciliation of the SPICE4C models with the modal test is discussed in Reference 12.

### 6.4.3 Control System Design

A two-tiered precision pointing control system, composed of a low-authority rate feedback system and a high authority global controller, was presented at the PDR (Ref. 20). Computer analysis performed using reasonable disturbance and noise models indicated that it met all of the PDR requirements, i.e., that it:

- Use HAC/LAC architecture,
- Attenuate 100μrad RMS LOS jitter by 40dB in simulation,
- Have a bandwidth ≤100Hz,
- Require RMS force ≤13N per actuator, and
- Require RMS travel ≤1.1 mm (assuming a 4.54kg proof mass) during closed loop operation.

#### 6.4.4 Simulation

A high-fidelity nonlinear time-domain simulation was generated that incorporated the SPICE structural model and provided time domain outputs for actuator and body dynamics. The simulation at PDR involved:

(1) Two rotational retarget commands and 12 disturbance inputs,

(2) 309 outputs including actuator dynamics, body dynamics, and positioning errors, and

(3) A total of 1000 states (400 SAVI and 600 SPICE structure).

It subsequently proved to be a valuable design tool and an important means of identifying causes and remedies when data anomalies were encountered.

#### 6.4.5 Integrated Structural Modeling (ISM)

The simulation of the SPICE structure was to have been transferred to the ISM environment in this task. ISM is an executive code that provides interconnection among several computer modeling codes and maintains file structures that facilitate the transfer of data among them. This task was deleted early in the subtask due to lack of funding.

#### 6.4.6 Design of Passive Damping Elements

Addition of tuned mass dampers, application of constrained surface layer damping to the tripod legs, and replacement of some bulkhead struts by viscoelastic struts or by viscous-damping D-struts were evaluated in combinations. Three concepts were developed to the level of detailed design of all required components:

(1) Passive I: Tuned mass dampers on each tripod leg, a constrained layer treatment on each leg, and damping struts replacing six No. 3 struts in the bulkhead

(2) Passive II, Concept 1: Constrained layer treatment on each tripod leg, damping struts replacing 60 of the bulkhead struts, and two tuned mass dampers located on the bulkhead

(3) Passive II, Concept 2: Constrained layer treatment on each tripod leg and damping struts replacing 94 of the bulkhead struts

The effectiveness of passive damping technology – both as a standalone system for reducing RMS LOS and as a stabilizer for a high gain HAC/LAC control system by damping of targeted spillover modes – was demonstrated in analyses.

Table 5. PMA preliminary design.

| | |
|---|---|
| Force (0 to peak) | 40N |
| Peak to peak stroke × proof mass | 7.4kg-cm |
| Power at 1 N RMS | 7W |
| First in-axis mode | <5Hz |
| First cross-axis mode | 150Hz |
| Frequency range | 0 - 500Hz |

6.4.7 Selection of PMAs

An exhaustive search of the literature and discussions with potential vendors showed that no off-the-shelf device could meet the SPICE specifications for the actuator/sensor subsystem. Analyses leading to a preliminary design with the characteristics shown in Table 5 were presented at the PDR (Ref. 20).

6.4.8 Analysis, Design, Fabrication, and Testing of New Truss Joints

In testing during subtask 02-02, the quick-connect joints were found to show hysteresis, to be nonlinear, and to dissipate too much energy. A new joint was designed that met all specifications and all of the quick-connect joints were replaced. Some struts in the SPICE structure connect on at least one end to aluminum brackets on the tripod legs or to aluminum cores inserted into the ends of the tripod legs. The threaded joints on these are different from the quick-connect joints. Testing had shown that these too did not meet the specifications for a precision modelable structure and so they were also replaced in this task. References 2 and 3 present the test results for the new SPICE truss links.

6.4.9 Design and Fabrication of Beam Expander Segments

The SAVI forward body was special test equipment that served the purposes of representing a beam expander to be isolated from aft-body disturbances. The SPICE experiments required that the LOS be calculated. It was determined that this would be done using spot measurements of the tilt and decentration of the optics mass-model segments. These elements were designed to be rigid in the frequency band of interest (≤100Hz). Successful designs were developed and the secondary and all seven primary segments were fabricated, tested, and installed on the structure in this task. The results of the testing of all of the segments are contained in Reference 7.

# 7.0 SPICE SUBTASK 02-04 - OPTICAL SENSING SYSTEM DESIGN

## 7.1 SUBTASK OBJECTIVE

The OSS was to be designed to meet the requirements developed in subtask 02-01.

## 7.2 PERIOD OF PERFORMANCE

Subtask 02-04 was active from 4 January 1990 through 27 September 1991.

## 7.3 SUBTASK APPROACH

Analyses and laboratory measurements were performed to establish the final design of the PMRS, the SMRS, and the SMTS. Engineering drawings were prepared for each of the optical sensors. Calibration and alignment procedures were developed. The vibration environment in which the sensors would operate was determined and analytical estimates of the atmospheric turbulence to be expected in the primary to secondary path were performed.

## 7.4 SUBTASK RESULTS AND DISCUSSION

The design of the OSS was brought to near-final form in this subtask. Major improvements to the prototype rotation sensors included increased signal power and broadening of the sensor beams. Trade studies were performed to maximize OSS signal-to-noise ratio (Table 6).

Table 6. OSS subtask 02-04 trade study results (selection underlined)

| Selection | Rationale |
|---|---|
| <u>Position sensitive detectors</u> v. quadrant cell detectors | Greater linear range |
| Detector size (2 × 2, <u>4 × 4</u>, 10 × 10mm) | Best combination of low noise, low sensitivity to optical aberrations in beam train |
| <u>CW</u> v. pulsed lasers | More photons, narrow FOV handles stray light |
| <u>Spatial beam separation</u> v. beam splitter | More photons to detector |

As described in subsection 2.2, each of the sensor units of the OSS projects a laser beam to a reflective element mounted on a mirror mass simulator. The original design used a single HeNe laser beam that was divided nine ways and transmitted via optical fibers to the sensors. Limitations of the laser and fiber optic losses led to consideration of the feasibility of installing a separate laser source in each of the sensor boxes. Visible pig-tailed laser diode assemblies manufactured by Seastar Optical Systems, Sydney, BC, Canada were identified as suitable for this purpose. One of the units failed soon after installation but its replacement and all of the

others performed well to the end of the program. The detailed tradeoff between a single HeNe laser and the individual diodes is summarized in Table 7 which was adapted from Reference 23, the final report of Subtask 02-04.

The linear ranges of the OSS sensors was increased significantly by the use of position sensitive detectors purchased from On-Trak Photonics, Lake Forest, CA instead of the usual quadrant cell detectors. The OSS electronics boards were custom-built by On-Trak with three gain settings ("$\times 1, \times 10, \times 100$") that allowed output signals to be kept in the ±10V range.

Analysis performed in Subtask 02-04 indicated that, although atmospheric turbulence in the paths of the SMTS and SMRS beams would be the dominant optical sensor noise, it would not exceed the PDR error budget of 0.2μrad (see Ref. 20).

The engineering drawing package for the final OSS design was completed in Subtask 02-04.

Table 7. Detailed tradeoff between single HeNe laser and nine diode lasers.

| | Single HeNe | Nine Laser Diodes |
|---|---|---|
| Requires Beam Splitters? | Yes | No |
| Requires Alignment? | Yes | No |
| Modularity | Low | High |
| Static and Surge Sensitive? | No | Yes |
| Total Optical Power (mW) | 15 | 36 |
| Wall plug Efficiency (%) | 2 | 20 |
| Electrical Power (mW) | 750 | 180 |
| Wavelength (nm) | 632.8 | 670.0 |
| Detector Response at Wavelength | 0.43 | 0.37 |
| AC Operation Possible? | Yes | No (Yes w/ chopper) |
| Cost Estimate (Including Couplers) | $8300 | $5000 |

# 8.0 SPICE SUBTASK 02-05 - ZENITH STAR SUPPORT EXPERIMENT DESIGN

## 8.1 SUBTASK OBJECTIVE

This subtask's objectives were to identify, assess, and design experiments that could be performed on SPICE hardware to support the Zenith Star Program.

## 8.2 PERIOD OF PERFORMANCE

Subtask 02-05 was active from 11 July 1990 through 11 November 1990.

## 8.3 SUBTASK APPROACH

Experimental proposals were sought in four areas:

(1) Isolation between a high energy laser device and a beam expander,
(2) Evaluation of proposed Zenith Star pointing and tracking control systems,
(3) Use of advanced materials and passive damping in a high energy laser system, and
(4) Characterization of vibrational disturbances, especially those due to coolant flow in a cooled secondary mirror.

The proposals were expanded to include technical detail and cost and schedule estimates for supporting the three Zenith Star experiments:

- ALPHA-LAMP Integration (ALI),
- Space Laser Experiment (SLE), and
- Complementary Space Experiment (CSE).

## 8.4 SUBTASK RESULTS AND DISCUSSION

Table 8 lists the proposed experiments, their ratings from Zenith Star senior technical personnel, and some brief comments. Reference 24 includes detailed descriptions of all of the 14 proposals.

Table 8. Proposed Zenith Star support experiments

| Experiment | Rating | Comment |
|---|---|---|
| **1.0 Isolation** | **2** | |
| 1.1 Passive isolation of a space-based laser component | Low | Already understood well enough for Zenith Star |
| 1.2 Isolation of a beam expander | Medium | Of potential use to a CSE or SLE |
| 1.3 Further SAVI research | High | Vital to success of Zenith Star flight experiment |
| **2.0 Pointing/Tracking Control Evaluation** | **4** | |
| 2.1 Active control of primary mirror segments | Low | This is within the scope of ALI |
| 2.2 ALI primary mirror-secondary mirror alignment system | Medium | |
| 2.3 High performance slewing of beam exp. | Medium | Best of 2.0: application to Zenith Star flight experiments |
| 2.4 Separate aperture tracker effects | Low | Not important - optical boresighting is used |
| 2.5 Smart struts in Zenith Star beam expander | Low | Zenith Star has no obvious need of this |
| **3.0 Advanced Materials / Passive Damping** | **3** | |
| 3.1 Advanced Composite Materials | High | Useful in design of damped structures |
| 3.2 Passive damping of tripod modes | Medium | ALI will apparently require this technology |
| 3.3 Passive damping of mirror mounts | Low | If "set and forget" proves inadequate, would go active |
| **4.0 Disturbance Characterization** | **1** | |
| 4.1 Admittance Modeling - passive structure | High | Very important to both flight experiments and to ALI |
| 4.2 Admittance Modeling - active structure | Low | Zenith Star flight experiments are not active structures |
| 4.3 Coolant flow disturbances from computational fluid dynamics | High | Very important to both flight experiments and to ALI |

# 9.0 SPICE SUBTASK 02-06 - ALTAIR HARDWARE AND FACILITY IDENTIFICATION

## 9.1 SUBTASK OBJECTIVE

The objective of this subtask was to provide assistance in testing, disassembling, shipping to the Phillips Laboratory, reassembling, and re-testing of equipment being transitioned from the Starlab program to the ALTAIR Program.

## 9.2 PERIOD OF PERFORMANCE

Subtask 02-06 was active from 8 February 1991 through 15 December 1991.

## 9.3 SUBTASK APPROACH

SPICE tasks and Starlab shutdown tasks were dovetailed to bring about the documenting, disassembly, shipping, and re-assembly of the ALTAIR equipment.

## 9.4 SUBTASK RESULTS AND DISCUSSION

Testing was performed on the five off-axis parabolic mirrors and the telescope that were to be transferred from the Starlab program to the Altair program. Deterioration of the telescope primary was found to be due to pinholes in the overcoat that allowed air to reach and oxidize parts of the silver layer.

# 10.0 SPICE SUBTASK 02-07 - ADVANCED MATERIAL TUBES INSERTION

## 10.1 SUBTASK OBJECTIVE

The objectives of Subtask 02-07 were to design and fabricate collars needed to integrate existing graphite/aluminum tubes into the SPICE structure.

## 10.2 PERIOD OF PERFORMANCE

Subtask 02-07 was to have begun on 3 September 1991. Budgetary constraints led the customer to cancel this subtask before any expenditures were made on it.

## 10.3 SUBTASK APPROACH

The two technical tasks identified for the subtask were:

(1) Analyses to determine where to place the graphite/aluminum tubes to maximize their effect on the structure and to predict what the effect would be, and

(2) Design and fabrication of tube collars for attachment of the tubes to the node balls of the SPICE bulkhead truss, and assembly of prototype links. A link is a tube with collars on either end suitable for attachment to the SPICE node balls and other fixtures. Assembly of the remaining links was to be performed by government personnel after training by the SPICE contractor team.

## 10.4 SUBTASK RESULTS AND DISCUSSION

The subtask was canceled before any action was taken.

# 11.0SPICE SUBTASK 02-08 - INVESTIGATION OF CRITICAL TECHNOLOGIES FOR ACTIVE STRUCTURAL CONTROL

## 11.1 SUBTASK OBJECTIVE

The objective of Subtask 02-08 was to perform all of the hardware and software development and testing required to prepare for the Precision Pointing Experiment.

## 11.2 PERIOD OF PERFORMANCE

Subtask 02-08 was active from 4 December 1991 through 17 April 1992.

## 11.3 SUBTASK APPROACH

The effort was divided into five technical tasks:

(1) Development of software interfaces among the components of the real-time system (see Fig. 14),
(2) PDR control system discretization (see Ref. 20),
(3) PMA development,
(4) Passive components development, and
(5) Investigation of air-piston technology for a future pneumatic gravity offload.

## 11.4 SUBTASK RESULTS AND DISCUSSION

### 11.4.1 Development of Software Interfaces

All software interfaces between the real-time system computers were developed to the level required for the Precision Pointing Experiment, that is, it was demonstrated that the system could handle 166 system states, 36 inputs, and 18 outputs at 1000Hz. The frame rate was a major challenge. The standard Star array processor interface protocol was found to be too slow to allow operation at the required frame rate. An alternative method was devised using "buffer pooling" in which the three Star compute heads have access to a common memory area. Details of the goals, organization, and operation of the control system software developed in Subtask 02–08 are in Reference 25 as are plans for addressing the real-time software issues still outstanding at the end of the subtask.

### 11.4.2 Control System Digitization

A digital control system was designed and analyzed using the SPICE 3 structural model. The design emphasized robustness in the presence of un-modeled spillover modes and 5% modeling errors. In analysis it attenuated open-loop disturbances by 50:1. Plans were made to implement it as a single matrix multiply in the Star array processor. Reference 25 discusses this phase of the HAC/LAC control system development in detail.

### 11.4.3 Proof Mass Actuator Development

The PMA design was taken to critical design review (CDR) level in Subtask 02-08. Table 9 shows the specifications driving the PMA development effort in this subtask.

Table 9. SPICE PMA specifications at CDR.

| | |
|---|---|
| Force | 36N zero to peak |
| Stroke | 55kg-mm peak-to-peak stroke-proof mass product |
| Accuracy | 1% nominal gain, 3% linearity |
| Dynamics | 500Hz bandwidth |
| Mechanical | • In-axis mode frequency = 5Hz ± 2%<br>• All other suspension mode frequencies >150Hz<br>• No stiction sources |
| Gravity | No bias power required in any orientation |
| Sensors | • Proof mass stroke position<br>• Housing acceleration<br>• Proof mass acceleration<br>• Bobbin temperature |

Note the large difference between the in-axis frequency tolerance in Table 9 (±2%) and the corresponding final PMA specifications shown in Table 2 (±20%). Difficulties in manufacturing the flexures from which the PMAs are suspended led to a decision to relax the mechanical uniformity requirement and to then electronically adjust the in-axis resonant frequencies to 5.0Hz.

Most of the technical issues involved in developing PMAs that were larger in stroke and force capacity than any former models were resolved by the end of this subtask. Prototype testing was initiated. Earlier PMAs had been smaller and attempts to scale their designs to SPICE force levels encountered several challenges. The voice coil force actuator showed nonlinearity that had not been a problem in models with lower NI (ampere-turn) values. The suspension flexure specifications were unprecedented in both in-axis linearity and cross-axis stiffness and it

became apparent that measures that improved one of these generally tended to make the other worse. The details of the resolution of these issues were deferred to Subtask 02-09.

### 11.4.4 Passive Component Development

Two kinds of passive damping elements, the V-strut and the D-strut, were designed, fabricated, and tested in the laboratory. The former uses shear in a layer of viscoelastic material to dissipate energy; energy is dissipated in a viscous fluid in the latter design. The V-strut as designed was found to be satisfactory for SPICE purposes. The D-strut tested was found to require more joint stiffness. Design optimization was not performed in this task. Reference 17 contains design and analysis methodology and results, test results, and conclusions concerning the use of passive damping technology in SPICE.

### 11.4.5 Air-Piston Technology for Pneumatic Gravity Offload

A 4.00-in-bore frictionless air piston, a 0.71-scale version of the units required for a SPICE pneumatic floor-standing gravity offload system, was demonstrated by showing that no friction occurred when the piston supported a load and its cylinder was pressurized to equilibrium. References 27 and 28 are, respectively, the test plan and test report for this task.

# 12.0 SUBTASK 02-09 - PRECISION POINTING EXPERIMENT (PPE), PHASE I

## 12.1 SUBTASK OBJECTIVES

The objective of this subtask was to demonstrate attenuation by the HAC/LAC control system of the effects of disturbances input to the SPICE structure. (Integration of passive technology into the SPICE structure and demonstration of HAC/LAC passive attenuation were intended to be accomplished in a future subtask, PPE, Phase II. However, due to budgetary constraints, the SPICE contract was terminated prior to implementation of Phase II.)

## 12.2 PERIOD OF PERFORMANCE

Subtask 02-09 was active from 4 February 1992 through 23 September 1993.

## 12.3 SUBTASK APPROACH

Ten technical task areas were identified:

(1) Resolution of remaining PMA technical issues,
(2) Laboratory operations,
(3) PPE controls design,
(4) PPE controls support,
(5) Maintenance and use of a detailed simulation of the integrated SPICE system,
(6) Planning and performance of open-loop and closed-loop tests,
(7) System engineering,
(8) Fabrication, testing, and installation of the OSS,
(9) Development and implementation of real-time and post-processing software, and
(10) Development and maintenance of a structural model of the SPICE test article.

All of these tasks were aimed directly at completing the HAC/LAC disturbance attenuation demonstration for which past subtasks had laid the groundwork.

## 12.4 SUBTASK RESULTS

Reference 16 contains more detail on all of the task areas discussed in this section.

### 12.4.1 Resolution of PMA Technical Issues

The complex development project that had begun in Subtask 02-01 with the establishing of preliminary requirements for the PMAs and continued through Subtasks 02-03 and 02-08 was completed when 18 identical PMA units were installed on the SPICE structure. The major

outstanding issues at the conclusion of Subtask 02-08 concerned voice coil linearity and the in-axis linearity and cross-axis stiffness of the proof-mass suspension. Analyses were performed to determine the effects upon system goals of relaxation in some subsystem requirements. Reduction in the stroke over which the voice coil had to be linear was found to be consistent with system goals. Flexure design was the subject of intense effort that resulted in significant improvements in in-axis linearity and cross-axis stiffness. That effort also showed that meeting the original requirements was beyond the resources of the program. Reductions in the PMA requirements for flexure linearity and cross-axis stiffness were made only after modeling and simulation showed that system goals would not be significantly compromised thereby. The final results of the HAC/LAC tests discussed in subsection 12.4.6 attest to the value of thorough analysis to guide review of subsystem requirements. The design iterations with the manufacturer, prototype testing, and analysis leading to the success of this critical subsystem are discussed in Reference 9.

### 12.4.2 Laboratory Operations

This task consisted of tying all the disciplines and subsystems into a cohesive whole. The interface electronics discussed in section 2.11 were completed under this task (see Ref. 18). Standardization of sign conventions, numbering sequences, signal scaling and polarity, coordinate frames, filtering, and other such parameters was established by the generation of a conventions diagram (Ref. 28). Routine essentials such as sensor calibration and alignment were also performed under laboratory operations.

### 12.4.3 Precision Pointing Experiment Controls Design

This task's goal was to develop the HAC/LAC control system to Critical Design Review (CDR) level. The goal of the CDR system was a reduction of RMS LOS jitter by a factor of 50. The HAC was redesigned to the SPICE4 structural model (Ref. 29) and developed to a near-final version (Ref. 30) that resulted in 77:1 attenuation in simulation.

### 12.4.4 PPE Controls Support

Task 4 consisted of analytical support for the three test series described in subsection 12.4.6 and refinement of the control system design as relevant test data became available. An analytical highlight of this task was the derivation of a means of extracting atmospheric turbulence spectra using a covariance analysis applied to the x-axes of the two SMTSs and the y-axis of the SMRS (Ref. 31). A planned series of measurements of OSS noise from air turbulence using angular displacement sensors (ADSs) was deleted when the ADSs proved inadequate. Therefore, the

derived method was of great importance in showing that, even with the long unshielded air paths between primary and secondary, the OSS met the requirement that its RMS noise be <200 nrad. The analytical demonstration that the LAC would be stable was also performed in this task (Ref. 33).

### 12.4.5 Simulation

This task supported the maintenance and use of a high fidelity, nonlinear time-domain computer model of the SPICE hardware. At intervals throughout the program, the full model was used to verify system stability and performance when sampling, quantization, nonlinearities, hardware high and low pass filters, etc., were introduced.

### 12.4.6 Testing

The PPE, Phase I test sequences spanned nearly a year and were the subject of planning and documentation efforts as thorough as those undertaken for the design of the hardware itself. The three PPE test sequences, the open-loop tests, the frequency response function (FRF)/LAC tests, and the HAC/LAC tests, were part of the SPICE overall plan to reach PPE, Phase II goals. Figure 15 the PPE test sequences.

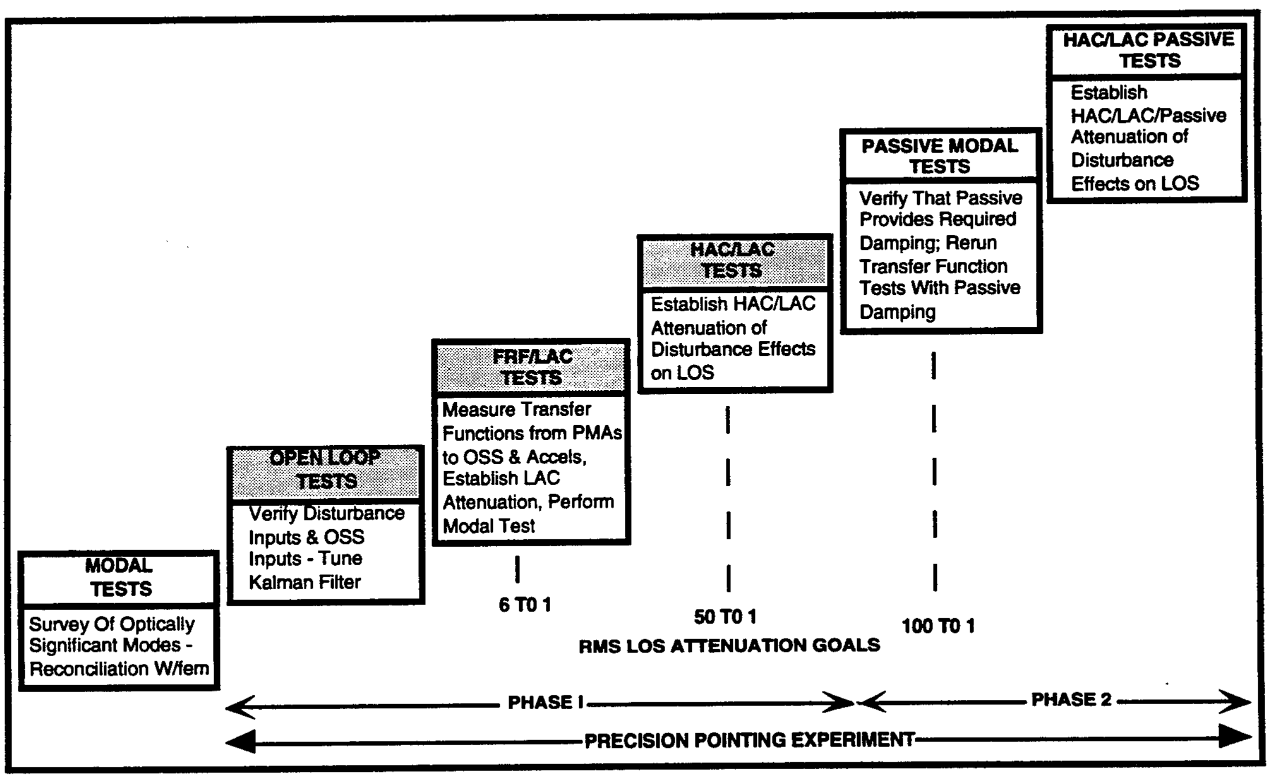


Figure 15. The SPICE test sequences with their objectives and goals.

The objectives of the open-loop tests centered around characterization of the structure, the system sensors, and the laboratory environment (Ref. 34). Detailed FRFs were taken from the disturbance sources to the system sensors. These tests were performed while the PMAs were still being built and provided validation of the open-loop models that supported the final design of the control system. The open-loop test results are documented extensively in Reference 35.

The next test sequence was called the FRF/LAC tests because it combined the functions of two test sequences from an earlier plan. Reference 36 is the final test plan for the combined sequence. The 18 PMAs were installed on the structure at the beginning of these tests. The tests covered detailed characterization and calibration of the PMAs as subassemblies, including closure of the local loops. With the loops closed, FRFs were taken from the actuators to the sensors. These FRFs were the last vital piece of data to be used in verifying the design of the HAC system. In addition, to quantify the effect that the installation of the PMAs had on the structure, a new modal test was performed on the structure to provide data for correlation with the final NASTRAN model. The FRF/LAC tests are extensively documented in Reference 37.

In the final test sequence, the HAC/LAC tests, the system was characterized with all loops closed. The tests included not only studies of global stability and performance, but also the measurement of closed-loop FRFs which allowed visibility into the inner workings of the system and detailed comparison to analytical models (Ref. 38). At the end of the HAC/LAC tests, the HAC/LAC system achieved 77:1 attenuation of the effect of input disturbance forces in the band 5 - 500Hz by active control alone. The final design of the HAC system and the results of the HAC testing are presented in Section 3.0 of Reference 16. Figure 16 shows three minutes of LOS data. After one minute of open-loop operation, which produced the large outer dark area, the local and LAC loops were closed. The RMS LOS decreased by a factor of ~8.5. The HAC was closed after the second minute, reducing the RMS LOS by a further factor of ~8.5.

12.4.7 System Engineering

This task provided direction to the others. The flow-down and flow-up process between system requirements and subsystem requirements was performed under this task. System engineering also kept the Precision Pointing Experiment focused on its goals. For example, the original specifications for the PMAs could not be met and modifications that brought the units closer to one of the specifications often entailed losing ground in another area. Specification changes had to be made that, as much as possible, retained system performance goals. The chief system

engineer identified and coordinated a series of analyses that resulted in PMAs that enabled SPICE to meet the system-level attenuation goals.

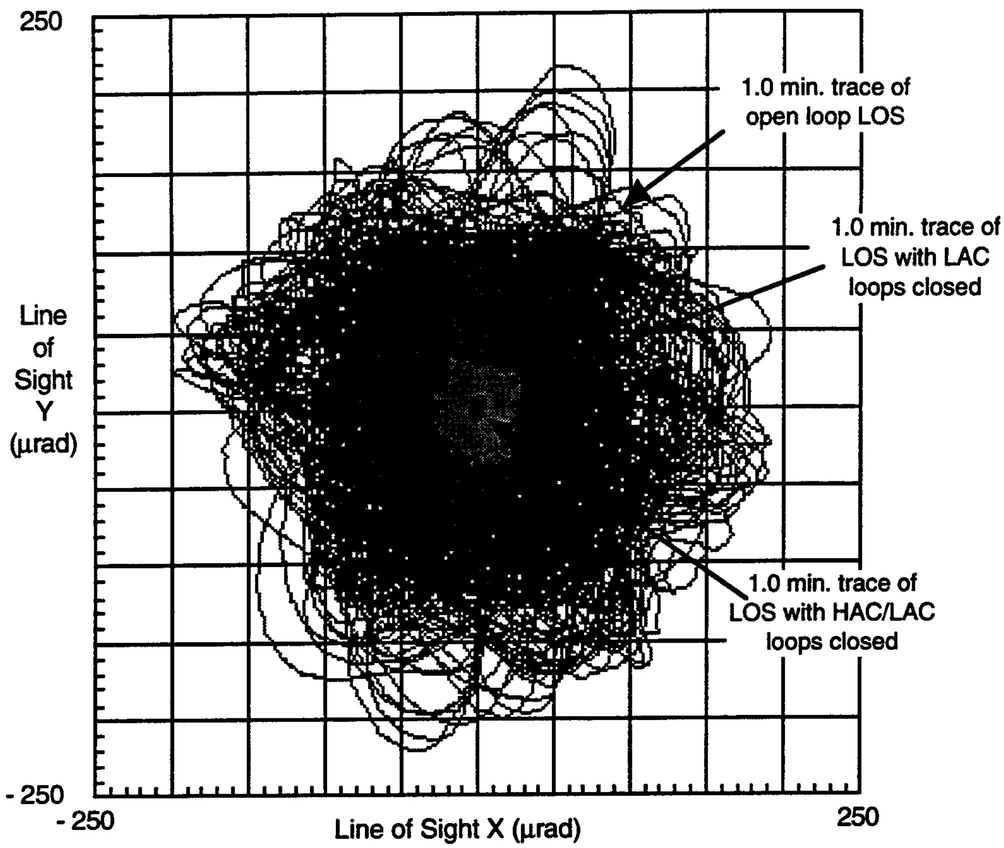


Figure 16. LAC attenuates open loop LOS disturbance, HAC/LAC attenuates it further.

12.4.8 Fabrication and Installation of the OSS

The fabrication of the nine sensor boxes that comprise the OSS and their calibration and integration into the SPICE structure was completed in this task. The sensor boxes were designed to have no resonances below 100Hz to avoid having their dynamics corrupt the tilt and decentration measurements. In bench testing, an unsuspected resonance between 30 and 40Hz was found that was traced to the mount for the holder of the optical fiber through which the beam left the box. A gusset designed to remedy the situation was successful in increasing the frequency of the lowest mode of the mount to 175Hz.

The alignment of the sensor boxes with the reflective elements on the mirror mass simulators was performed on the structure. The mounting holes were drilled after the optical alignment procedures were completed to ensure that they were properly located.

Reference 22 summarizes the development, fabrication, calibration, and installation of this critical subsystem. The devices achieved the required LOS dynamic range. They were able to measure LOS jitter >100μrad RMS and had a measured noise floor <200nrad RMS.

12.4.9 Software Development and Implementation

The complex software required for the operation of the HAC/LAC control system (see Subsection 2.3.10) was completed on this subtask. The development spanned several subtasks. The SPICE software development that was crucial to the smooth functioning of the real-time system is documented in Reference 16. Users manuals were also developed for the SPICE software (Ref. 39) and data management utilities (Ref. 40).

12.4.10 Structural Modeling

The latest SPICE finite element models, the SPICE5 models, were reconciled to the full modal test performed as part of the FRF/LAC tests. The SPICE5 models are evolutionary models derived from the SPICE4 model series which were based upon the modal test of subtask 02-03. Two SPICE5 models, SPICE5A and SPICE5G, were developed (Ref. 13). The SPICE5A model considers the SPICE beam expander structure to be fully free-free with no connection to ground (i.e., the same boundary conditions considered in the previous SPICE models). The SPICE5G model is identical to the SPICE5A model with the exception of

- Inclusion of the gravity off-load suspension rod/ZSRM representation (connected to ground), and
- Inclusion of stiffness effects of the secondary mirror disturbance shaker stingers (connected to ground).

In the HAC demonstration, disturbances were input to the SPICE structure at the SAVI vertices, to represent aft-body disturbances, and by shakers attached to the secondary, to represent coolant flow. For discussion of the excellent model/test correlation achieved in the SPICE5 models, see Reference 13.

# 13.0SPICE SUBTASK 02-10 - ABL RISK REDUCTION

## 13.1 SUBTASK OBJECTIVE

This subtask's objective was to provide support for development and assessment of airborne laser (ABL) system beam control subsystem concepts.

## 13.2 PERIOD OF PERFORMANCE

Subtask 02-10 was active from 6 July 1992 through 15 December 1992.

## 13.3 SUBTASK APPROACH

Two technical tasks were identified:

(1) System Concepts
(2) Subsystem Concepts

## 13.4 SUBTASK RESULTS AND DISCUSSION

System requirements provided by the Phillips Laboratory were used to develop an engagement timeline and a baseline beam control system. The system requirements were then flowed down to subsystem requirements and trade studies were performed to select the concept in each subsystem category that best met the relevant requirements. Selected subsystems included top-mounted turret location, separate-aperture fine tracker, Hartmann wavefront sensor, Nd-YAG illuminator, buried wedge aperture-sharing element, and uncooled optics. Reference 41 is a report of the results of the study.

# 14.0 SPICE SUBTASK 02-11 - SURVEILLANCE TEST BED GLOBAL PROTECTION AGAINST LIMITED STRIKE SUPPORT

## 14.1 SUBTASK OBJECTIVE

This objective of this subtask was to provide support to the Surveillance Test Bed (STB) project.

## 14.2 PERIOD OF PERFORMANCE

Subtask 02-11 was active from 13 August 1992 through 30 October 1992.

## 14.3 SUBTASK APPROACH

Two tasks were identified:

(1) Review and support the requirement and interface definitions of the STB Global Protection Against Limited Strike test article, and

(2) Review the adequacy of the STB demonstrations and assist in the STB test article selection.

## 14.4 SUBTASK RESULTS AND DISCUSSION

This study identified required modifications in the STB specification documents in the sensor crossing model, the composite scene generation model, and the optical threat-object signatures. In addition, a preliminary software design for the tracking test article and a preliminary tracking algorithm taxonomy are presented in considerable detail in the final report of this subtask (Ref. 42).

# 15.0SPICE SUBTASK 02-12 - SYSTEM IDENTIFICATION INVESTIGATIONS & SYSTEM UPGRADES

## 15.1 SUBTASK OBJECTIVES

This subtask had two objectives: (1)- to develop system identification methods capable of autonomously generating state space models for use with the Precision Pointing Experiment control system, and (2)- to design a modification to the flexible mode control system to include control of the rigid body modes.

## 15.2 PERIOD OF PERFORMANCE

Subtask 02-12 was active from 6 January 1994 through 15 January 1995.

## 15.3 SUBTASK APPROACH

Two tasks were identified:

(1) System identification investigation, with the particular requirement that the government-owned Leuven Measurement System (LMS) be among the methods included in the investigation, and

(2) Design of a modification to the flexible mode control system to include control of the rigid body modes.

## 15.4 SUBTASK RESULTS AND DISCUSSION

### 15.4.1 System Identification

Two methods were investigated in the system identification task: the LMS-based method and a method called principal gain tracking (PGT).

In the LMS method, burst random excitation was input at each of the three SAVI vertices. The output consisted of 57 measurements:

- OSS measurements: primary segment tilts, secondary tilt and displacement (18)
- PMA housing rates (18)
- Displacements of proof masses within their respective housings (18)
- Structural accelerations at the SAVI vertices (3)

Data were taken in two bands, 5 - 30Hz and 30 - 60Hz. The LMS system calculated auto- and cross-spectra and, from these spectra, FRFs from each of the PMAs and the SAVI vertices to all

57 outputs. Curve-fitting routines in the LMS package then provided the modal frequencies, dampings, and shapes.

Based on the resulting structural model, a HAC/LAC control system was designed that, on 23 September 1994, attenuated LOS jitter due to input disturbances by ~50:1 in the 1 - 128Hz band. This result cannot be compared directly with results reported in section 12.4.6 because conditions were not the same in subtasks 02-09 and 02-12. In tests run in the former, disturbance forces were input to the structure by the three SAVI actuator resultants and by three mutually perpendicular shakers attached to the secondary. In subtask 02-12, the shakers were not attached to the structure and only the SAVI actuators were used to input disturbance forces. Both sets of disturbance forces produced 100μrad RMS LOS error with all control loops open.

To provide a basis of comparison, the HAC designed using the SPICE5A finite element model was tested with the 02-12 disturbance set. Approximately 91:1 attenuation was achieved in the same frequency band, i.e., 1 - 128Hz.

In the first series of PGT tests, sine wave disturbances were input at all 21 actuators simultaneously and only the OSS measurements and the PMA housing rates were recorded. Data were taken every 0.1Hz from 2 - 60 Hz. The essence of the PGT method is that each complex vector of input gains and phases is proportional to a singular vector of the complex transfer function matrix. The transfer function matrix is, of course, not known in advance. In practice each of the 21 input disturbances sets at frequency f is a constant times a singular vector of the transfer function matrix at $f - \Delta f$. Data taking requires far more time than does the LMS method. However, a model was extracted from only 36 sensor signals. The model was not robust in simulation and it was concluded that the data did not permit the PMA modes to be described with sufficient accuracy.

A second series of PGT tests was performed in which, in addition to the OSS and PMA housing rate signals, data were taken to provide the relative velocities of proof masses and their respective housings (so 54 output degrees of freedom were used). For frequency ≤ 13Hz, the LVDT measurements of proof mass displacements were used; for frequency ≥ 13Hz, the differential accelerations of housings and proof masses were recorded. The model derived from these data performed very well, although not as well as the SPICE5A HAC. Table 10 summarizes the results of a series of disturbance attenuation tests that was conducted on January 3, 1995. In quiescent tests no external disturbances were applied; in 100μrad tests, the SAVI actuators were used as described above.

This task demonstrated that the SPICE structure can be controlled with a high-gain HAC developed using a model derived from a system identification method. Nonetheless, the model to beat remains that derived from Finite Element Modeling. With modest improvements, we believe that system identification derived models will perform as well as correlated finite element models.

Table 10. Results of PGT HAC tests.

| HAC Designed Using | Disturbance Set | LOS Residual (μrad) in 5-128 Hz Band | | LOS Residual (μrad) in 1-128 Hz Band | |
|---|---|---|---|---|---|
| | | X-axis | Y-axis | X-axis | Y-axis |
| SPICE5A | Quiescent | 0.29 | 0.26 | 0.34 | 0.34 |
| PGT | Quiescent | 0.27 | 0.22 | 0.30 | 0.26 |
| SPICE5A | 100μrad | 0.86 | 0.69 | 1.18 | 1.02 |
| PGT | 100μrad | 1.08 | 0.99 | 1.39 | 1.32 |

15.4.2 Modification to the Control System to Include Control of the Rigid Body Modes.

Key features of this design effort include:

(1) For the purposes of this design effort, rigid-body control was interpreted to mean control of the SAVI magnetic actuator gaps.

(2) The nominal plant used for the HAC design included:

a) the standard SPICE structure as in the Precision Pointing Experiment,

b) the high-gain SAVI rigid-body controller,

c) three SAVI disturbances as described above, with 1-to-10Hz shaping filters,

d) 42 measurements consisting of 18 PMA housing rates, 18 OSS, and 6 SAVI gaps,

e) 24 actuators consisting of 18 PMAs and 6 SAVI actuators.

f) PMA local-loop and LAC rate-feedback damping as in the Precision Pointing Experiment.

(3) A HAC regulator was designed to reduce SAVI gap motion using only the SAVI actuators. This control loop essentially boosts the function of the nominal SAVI rigid-body servo. The nominal SAVI servo is limited by a digital sample rate of 25Hz, and unmodeled interaction with the flexible modes. In the Gap HAC, global control uses knowledge of the structural modes and a high digital sample rate to augment the nominal SAVI servo. The nominal servo itself is not altered.

(4) A HAC regulator was designed to reduce LOS as measured by the OSS using both the PMAs and SAVI actuators.

(5) A common Kalman estimator is designed for both the Gap HAC and the LOS HAC.

(6) The entire control system, consisting of the Kalman estimator, the Gap HAC regulator, the LOS HAC regulator, and the OSS high-pass filters, is implemented as a single matrix multiplication within the STAR processor.

In essence, the HAC was designed around a plant that included an augmented SAVI rigid body servo. The design was successful and robust in analysis. Reference 43 contains a detailed discussion of all of the efforts. In particular it details the modifications required to implement a HAC that includes control of the rigid body modes of the SPICE structure.

## 16.0 SPICE SUBTASK 03-01 - COMPUTER ROOM INSTALLATION

### 16.1 SUBTASK OBJECTIVE

The control room in Building 765 was to be modified to accommodate a computer room to house government-owned computers and related equipment.

### 16.2 PERIOD OF PERFORMANCE

Subtask 03-01 was active from 7 April 1989 through 7 July 1989.

### 16.3 SUBTASK APPROACH

The tasks of this subtask were identified as:

(1) Develop design requirements from the specifications of the computers and other equipment,

(2) Evaluate existing power-conditioning and temperature-control equipment for their ability to meet the requirements,

(3) Present the completed design and specifications to the government for approval, and

(4) Upon receipt of approval perform the required modifications to the control room.

### 16.4 SUBTASK RESULTS AND DISCUSSION

The four tasks were performed as planned. Upon approval of the redesign, the required modifications to the control room were made. The resulting facility proved adequate to house all required computer equipment.

# 17.0SPICE SUBTASK 03-02 - ISOLATION CHAMBER DESIGN

## 17.1 SUBTASK OBJECTIVE

The objective of this subtask was to design an isolation chamber to provide environmental control for experiments on the SPICE apparatus.

## 17.2 PERIOD OF PERFORMANCE

Subtask 03-02 was active from 24 September 1990 through 17 December 1990.

## 17.3 SUBTASK APPROACH

The subtask was divided into seven technical tasks:

(1) Define the concept,
(2) Perform trade-off analyses,
(3) Develop design approach and initial cost estimates,
(4) Design the isolation chamber,
(5) Formulate cost estimates for isolation chamber construction,
(6) Determine building 765 modification requirements, and
(7) Formulate cost estimates for building 765 modification.

## 17.4 SUBTASK RESULTS AND DISCUSSION

At the conceptual design review (see Ref. 44), concepts and alternatives were presented for control of acoustic noise, temperature, humidity, and fire safety issues. The isolation chamber requirements derived in subtask 02-01 were used in the preparation of these concepts. Details of mechanical, plumbing, and electrical requirements and cost estimates were provided at the review. Due to funding limitations, the isolation chamber was not constructed.

# 18.0 SPICE SUBTASK 03-03 - SPICE FACILITY SUPPORT

## 18.1 SUBTASK OBJECTIVE

The objectives of this subtask were to provide, as required, maintenance, improvement and operation of SPICE project facilities, equipment, documentation, computer hardware, and software and upgrades to the real-time control system.

## 18.2 PERIOD OF PERFORMANCE

Subtask 03-03 was active from 24 November 1993 through 31 March 1995.

## 18.3 SUBTASK APPROACH

Two broad tasks were specified:

(1) Computer systems management and software upgrade, and

(2) Configuration, documentation, and asset management.

## 18.4 SUBTASK RESULTS AND DISCUSSION

Considerable upgrading of the real-time software was required in the late stages of SPICE because the real-time system had, in all experiments before subtask 02-12, been entered only once during a data session. Leaving the real-time controller had been equivalent to ending the session. The need to have a smooth interface with the PGT code running in the host VAX so that entry and exit in a loop could be effected required extensive modification of the software. A second major effort was directed toward offloading data preprocessing to the Star. Using an array processor this way was a challenging programming effort that cut weeks off the data-gathering. Reference 45 discusses the enhancements to the SPICE software that were developed in Subtask 03-03.

# 19.0 LESSONS LEARNED

## 19.1 REQUIREMENTS MODIFICATION

*When an initial set of requirements can not be met, do not adopt a share-the-pain approach to their modification.* Perform analyses in light of the knowledge gained since the initial requirements were adopted and see which can be relaxed without hurting program objectives. In the complex PMA development effort, it was concluded that the development of a flexure that could meet all of the original specifications would require more resources than were available and therefore it was necessary to make some concessions. Analyses showed that the system-level objectives could still be met with reductions in the PMA requirements for both flexure linearity and cross-axis stiffness. With these modifications to the specification, a final flexure design was developed that is similar to the original flexure geometry devised by the Harris Company, Melbourne, Florida, but with a modified web shape and thickness.

## 19.2 CONVENTIONS AND COORDINATES

*A well-maintained system master block diagram will save a program far more time and money than it costs.* The SPICE program established a master block diagram that defined, on a single E-sized sheet, all hardware conventions including signal names and numbers, scaling and polarity, coordinate frames, etc. Having this material available early and distributed to all members of the team avoided many of the usual problems during integration of subsystems. For example, the PMAs and the OSS sensors have local coordinate systems; their integration was facilitated by having standards already determined. Polarity problems were routinely identified and corrected. Copies of the master diagram were distributed to all engineers on SPICE and affixed to walls in the test cell and other program areas. Innumerable questions arising in engineering discussions were resolved at once by reference to the master diagram. The effort required to maintain it was not insignificant but it was dwarfed by the benefits it provided in eliminating confusion.

## 19.3 DATA MANAGEMENT PLANNING

*In a data-intensive experiment like SPICE, it is extremely important to consider in advance the amount of data to be generated and what will be done with it.* If nothing is planned for some of the data, there is no point in acquiring it. The impossibility of extracting and printing the results of some of the FRF tests in a reasonable time, much less evaluating them, led to realization of the necessity to automate the data review. The FRF scoring algorithm (see Ref. 36) and other data-evaluation tools were developed before the data became overwhelming.

## 19.4 MODELING REQUIREMENTS

*Detailed computer modeling of a complex experiment will more than pay for itself.* In at least two areas, the SPICE team learned about the need for even more computer modeling in an experiment that probably was better modeled than any similar experiment. The omission of the mass of the armatures of the secondary shakers caused the load cell measurements at the shaker drive points to be thought to contain anomalies. The omission was remedied but it could have caused a delay if SPICE analysis personnel had not identified the problem rapidly. The effect was found to be important only for very lightly damped modes. It was originally assumed that the SAVI controllers could be modeled without consideration of possible interaction with other elements of the SPICE structure. Unexpected low frequency behavior in FRFs was traced to interaction of SAVI with the secondary shakers. Unexpected damping of the first bending modes in the disturbance tuning tests was traced to SAVI interaction with the structure at high amplitude shaking. These test difficulties are all discussed in Reference 34.

It is difficult to see how all of this could have been reasonably foreseen. A related lesson probably is that no subsystem model should be considered exempt from reexamination when test anomalies are seen, even one as well documented as SAVI.

## 19.5 ELECTRONICS PARTS AND SUPPLIES

*Do not try to cut corners in interface electronics parts and supplies!* The following two observations from the SPICE program illustrate this:

- The methods used in SPICE required more expensive cables, connectors, and parts and labor to build interface circuitry, as well as other costs to correctly implement grounding, shielding, buffering, etc. The resulting clean data and freedom from the need to diagnose and repair ground loop problems every time a new scope was connected were ample compensation for the extra effort.
- The line engineer should have the authority to specify and purchase spares. He is best qualified to determine the type and quantity of spares to stock. Most spares do get used, are needed immediately when they do, and are least costly when included in the original order.

## 19.6 CALIBRATION

*Verify sensor calibrations* in situ, *especially if the sensor is a custom unit.* A calibration issue that arose during the FRF/LAC tests points to the need for such verification. The OSS was calibrated on the optical bench in a special test setup. When it was later suspected that the gain

in volts per radian or volts per meter might be incorrect (some system level data suggested this), a way was found to take calibration data in place on the structure. The data showed that all four axes of the SMTSs were in error by the same factor, and both axes of the SMRS also had identical errors. This indicated an error in the calibration reference, i.e., the bench test setup. After recalibration, several of the open-loop system-level tests had to be repeated. The ability to easily verify calibration *in-situ* should be designed into any custom sensor.

## 19.7 WORKING WITH OLD, UNRELIABLE EQUIPMENT

*It is unwise to plan an experimental procedure around a set of old sensors for which recent data are not available, and which cannot be calibrated.* The ADSs were made available as residual equipment from another government program. They were planned upon for measurements crucial to understanding atmospheric turbulence. In preparations for the tests, the ADS transfer functions were not found to be as advertised (see Ref. 34) in the manufacturer's literature and almost one-half of the channels on the three triaxial cubes were found to be dead. The SPICE team was fortunate that it's analyst was able to devise an alternative approach to measuring the effect of atmospheric turbulence on the LOS measurements.

## 19.8 NONPRECISION HARDWARE ON A PRECISION STRUCTURE

*Attaching unmodeled, nonprecision hardware to a precision structure can result in problems that are difficult to diagnose and that tend not to remain fixed.* The shaker stingers that input vibration to the secondary mirror mass simulator caused difficulties that were unanticipated and that tended to be discovered through anomalies in test data. The shaker stingers were initially regarded merely as devices that input forces to the structure along their axes. The significance of their cross-axis stiffness and damping was not considered. Moreover, remedies for these oversights tended not to be permanent because of the nonprecision nature of the stingers. A better method of introducing vibration into the secondary should have been devised during planning for the Precision Pointing Experiment. The hardware cost savings from using equipment that happened to be available was unimportant compared to the lost time.

## 19.9 INTERACTION WITH OTHER PROGRAMS

*Synergistic interactions with other R&D programs is difficult but can be achieved.* For example, the Zenith Star support subtask served to make Zenith Star and SPICE personnel more aware of each other's needs and capabilities. Perhaps a low-level effort of longer duration should supplement the short-burn brainstorming sessions. A program will reach out for new technology when it has a problem and not before.

## 19.10 TECHNICAL INTEGRATION MEETINGS

*Well-prepared regular presentations of results enhance the quality of a program in several ways.* The SPICE Technical Integration Meetings (held every 4-6 weeks) brought together people from different companies in different states often enough for team members to get to know each other's strengths and to become personally acquainted. This led to an understanding of the role of each individual, resulting in an integrated team that worked well together despite the inconvenience of long distances. The value of these weeks in supporting this type of personal and professional interaction even outweighed the value the Technical Integration Meetings as mechanisms of formal reporting to the government.

The week-long Technical Integration Meetings were open to invited guests which provided an opportunity for the SPICE team to present and discuss its results and plans with national experts in a variety of relevant disciplines.

## 19.11 THE SPICE INTEGRATED TEAM

*The SPICE integrated team approach was a major contributor to program success.* In SPICE, tasks were not assigned to a particular corporate team member. Instead, prime contractor and subcontractor personnel formed analysis, test, planning, etc. teams based entirely upon appropriateness of skills. Personnel still reported to their respective line organizations, but were fully integrated for program purposes. Task leadership was assigned to a Honeywell or a CSA Engineering person if he was the most knowledgeable in that area. Stimulating interchanges of ideas arose very naturally in the integrated team environment. Where it was appropriate, government personnel participated in several aspects of the program, particularly in the open discussions at which technical challenges were often resolved.

## 19.12 INTERFACE ELECTRONICS

*Good signal quality requires meticulous attention to the design of interface electronics.* Since the ultimate goal of the SPICE Precision Pointing Experiment was to demonstrate significant reductions in measured analog signals from the system sensors, it was of paramount importance that the noise-free transfer of analog signals throughout the system be given as much attention as the development of the sensors and actuators themselves. This has often been overlooked, and many otherwise well-conceived experiments have failed due to such factors as poor grounding and shielding. This type of mistake, once made, is usually prohibitively expensive to correct and results in low signal-to-noise ratios and generally poor data throughout the experiment. Furthermore, when an active control system with bandwidth near 60Hz is involved,

the huge spectral peaks at 60Hz so often explained away by experimentalists can be amplified, resulting in signal clipping and even instability. The 60Hz energy cannot be filtered without degrading the phase of the loop, which high bandwidth loops will not tolerate.

The SPICE program dealt with these issues from the beginning, ensuring by design that no sensor or component anywhere in the system was allowed to have a direct connection from signal to chassis ground. In a large distributed system like SPICE, in which many cables are more than 100ft long, this is the first step toward avoiding "ground loops." A single-point grounding philosophy was established early and rigidly maintained. In the SPICE system:

- Every command/telemetry signal was transmitted using balanced differential line drivers and receivers with three-conductor "twin-ax" cables,
- No 60Hz power was distributed anywhere on the structure (a direct current [DC] power bus drove local DC-to-DC converters for electronics supplies where needed), and
- All differential signals were buffered into a signal interface console where they were available to the Tustin analog-to-digital converters and to front panel access through appropriate anti-aliasing and isolation circuitry. The interface console also hosted the system's single point ground connection, and this ground was tied via heavy braid to the HP3565, the front-end computer of the modal system, located adjacent to it.

Extremely clean analog signals throughout the system resulted from these efforts. Electronic noise was ~1 to 2mv RMS, and no 60Hz spikes were observed on measured PSDs in any of the system-level tests.

## 20.0 CONCLUSIONS

The success of the SPICE program that culminated in achieving 77:1 reduction in the 5 to 500Hz band of RMS LOS jitter due to input disturbances was the result of a systematic approach to creation of a precision structure. As is clear from the somewhat historical perspective provided by the subtask summaries, required subsystems, including sensors and actuators capable of implementing the HAC/LAC control system, were identified and followed closely through fabrication and integration into the structure in a very systematic manner. Requirements were derived from thorough analyses that were updated whenever new data became available. Understanding of test--results including anomalies--remained the most important principle of the program.

## 21.0 RECOMMENDATIONS

Further experiments can and should be performed on the SPICE test bed. Specific recommendations include:

(1) The Precision Pointing Experiment, Phase II should be performed as depicted in Figure 15. The passive damping technology required for the next major advance in attenuation of disturbance effects through global control has already been developed in the SPICE program (subsection 11.4.4). Analysis has shown that a combined HAC/LAC/Passive control system will be a significant next step beyond HAC/LAC.

(2) Complete, install, and test the pneumatic gravity offload (subsection 2.5). The result will be improved traceability to a space-based telescope.

(3) Build upon the first steps toward development of autonomous system identification performed in Subtask 02-12 (see section 14). The benefits to a space-based system of being able to perform tests on itself using only its control system sensors and actuators and then to modify the control system are potentially very great, especially if interest in systems requiring pointing accuracy of ~100nrad returns.

## 22.0 ACRONYMS

| | |
|---|---|
| ADS | angular displacement sensor |
| ALI | ALPHA-LAMP integration |
| CDR | conceptual design review |
| CSE | complementary space experiment |
| DC | direct current |
| FRF | frequency response function |
| HAC | high authority control |
| LAC | low authority control |
| LOS | line of sight |
| LVDT | linear variable differential transformer |
| OSS | optical sensing system |
| LMS | Leuven measurement system |
| PDR | preliminary design review |
| PGT | principal gain tracking |
| PMA | proof mass actuator |
| PMRS | primary mirror rotation sensor |
| PSD | power spectral density |
| RMS | root-mean-square |
| SAVI | space active vibration isolation |
| SLE | space laser experiment |
| SMRS | secondary mirror rotation sensor |
| SMTS | secondary mirror translation sensor |
| SPICE | space integrated controls experiment |
| STB | surveillance test bed |
| ZSRM | zero spring-rate mechanism |

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